Extended Abstracts
from the

NASA Workshop on Scientific Requirements for Mitigation of Hazardous Comets and Asteroids

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held in Arlington, VA
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Erik Asphaug and Nalin Samarasinha, eds.
asphaug@es.ucsc.edu, nalin@noao.edu

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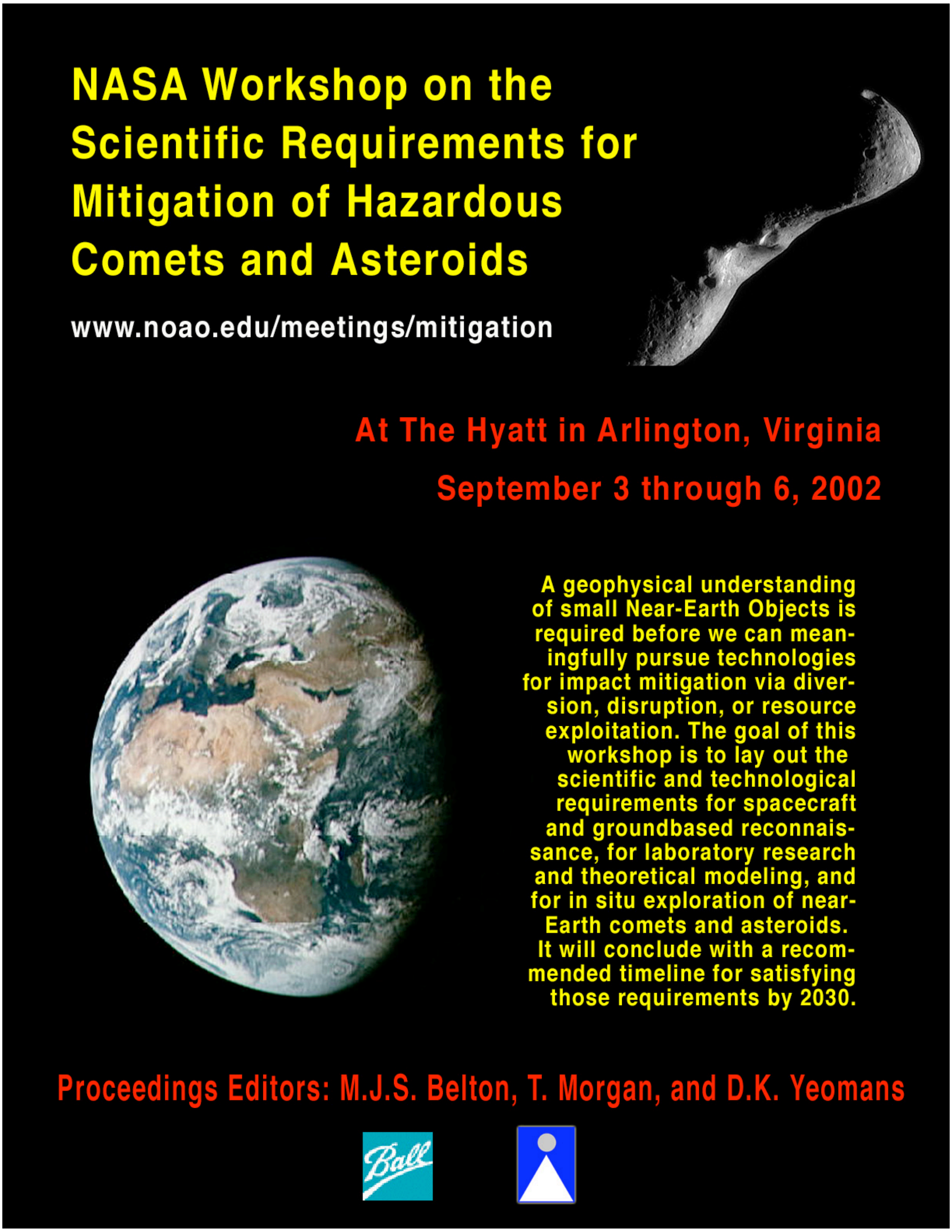

Workshop Poster (July 2002)

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In September 2002, NASA's Office of Space Science sponsored a workshop on *Scientific Requirements for Mitigation of Hazardous Comets and Asteroids*, attended by 70 scientists from around the world and 20 registered media participants. Peer reviewed invited proceedings from this workshop will be published by Cambridge University Press in late 2003; extended abstracts from both invited and contributed talks are included here. See http://www.noao.edu/meetings/mitigation for updates on the book publication and for other materials related to the workshop. This document will be archived at the above site, and may be updated in time with better formatting.

In addition to NASA's sponsorship, support from Ball Aerospace, NOAO, The University of Maryland, Lockheed Martin and SAIC helped make the workshop a success and is gratefully acknowledged.

On the following pages you will find the consensus statement that was released to the press on the final day of the workshop, followed by contributed extended abstracts in alphabetical order.

Erik Asphaug
University of California, Santa Cruz, CA

Nalin Samarasinha
National Optical Astronomy Observatory, Tucson, AZ

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Science Workshop Reveals Evolving Perspective on Asteroid Threat

For More Information:

Douglas Isbell
Public Information Officer
National Optical Astronomy Observatory
Phone: 520/318-8214
E-mail: disbell@noao.edu

Prof. Erik Asphaug
University of California at Santa Cruz
Phone: 831/459-2260
E-mail: asphaug@es.ucsc.edu

Direct measurements of the surface properties and interior structures of asteroids and comets should be fundamental elements of future spacecraft missions to these primitive solar system bodies, according to participants in a scientific workshop held in Arlington, VA, from September 3-6.

Such information is vitally important for preparing a variety of approaches for the diversion of Near-Earth Objects which may someday threaten Earth. Evidence presented at the workshop suggests that gentle thrusts applied for decades, rather than traditional explosives, are likely to be needed to change their orbital paths. This will require early detection together with knowledge of their geologic properties.

Sponsored by NASA, the workshop was designed to find common ground among researchers on the reconnaissance and exploration of Near-Earth Objects. “Unlike volcanoes or earthquakes, the NEO hazard was only recently identified, and we have just begun to understand its implications,” said meeting organizer Erik Asphaug of the University of California at Santa Cruz. “This is the only major natural hazard which can, in principle, be made predictable and even eliminated if we find the dangerous ones and learn how to modify their orbits over time.”

Astronomers have determined precise orbits and estimated the sizes of approximately 1,500 Near-Earth Objects (NEOs), according to conference presentations. More than 600 of the estimated 1,000 asteroids larger than one kilometer in diameter (a size that could cause widespread calamity on Earth) have been detected so far. This represents good progress toward the goal mandated by Congress for NASA to discover 90% of these objects by 2008. While no known asteroid is on collision course with Earth, ongoing detection should alert us to serious threats.

Significant topics of discussion at the workshop included large uncertainties in the state of scientific knowledge of asteroid surfaces, despite great advances in recent years. There is increasing evidence that most asteroids larger than a few hundred meters have complex interiors and may be loosely bound conglomerates which might resist explosive diversion. To almost everyone's surprise, about a sixth of NEOs are now observed to have moons, which would complicate any effort to change their orbits.

While scientific goals of researching the early history of the solar system and mitigation goals of protecting the Earth are very different, the kinds of asteroid studies needed to address both goals are largely identical, several participants noted. "Learning more about them is the first step," Asphaug said. Gathering a wide variety of measurements is critical for fully understanding the history and properties of NEOs, given their great diversity and their many observed dissimilarities from presumed analogues like the surface of the Moon.

Because we know so little, physical characterization was seen by researchers as going hand-in-hand with potentially useful technological developments. For example, a large, lightweight solar concentrator was discussed that could vaporize a small surface area for measurements of composition; thrust from the escaping material could be measured to test concepts for solar-powered asteroid deflection.

Because close-calls are far more likely than actual impacts, attendees also discussed the deployment of radio transponders for precision tracking of dangerous objects. Many researchers expressed the need for high-performance propulsion systems that could power a spacecraft to a rapid rendezvous with an NEO.

Ground-based observatories such as the proposed 8.4-meter Large Synoptic Survey Telescope (a high priority in the most recent Decadal Survey of astronomy by the National Academy of Sciences) can be effective tools to detect 80-90% of the NEO population down to a diameter of 300 meters within about a decade of full-time operations. A spacecraft orbiting close to the Sun and looking outward in tandem with such a telescope might reduce this time to five years. NEOs in this size range can cause widespread regional damage on Earth, although the workshop scientists agreed that the detailed effects of impacts of any size remain poorly understood.

Ground-based radar observations of close-approaching NEOs will also remain a uniquely important and flexible method to study a variety of objects, attendees agreed. Radar is capable of imaging and accurately tracking the closest Earth-approachers.

Few countries outside of the United States are spending significant resources on the NEO hazard, and this international imbalance must be remedied if the threat is to be fully understood within the next few decades, according to several speakers. For example, there are currently no active ground-based NEO searches in the Southern Hemisphere.

Despite the spectacular success of NASA’s recently concluded Near Earth Asteroid Rendezvous mission, and excitement surrounding Japan’s upcoming MUSES-C mission (the first-ever sample return from an asteroid, to be launched in December), researchers agreed that more substantial investigations are required if we are to learn how to change an asteroid’s orbit.

Scientists must take better advantage of opportunities to explain new detections and their related risks to the media and the public, attendees agreed. With advanced search systems coming on line, asteroids will be discovered at an increasing rate, with orbits which may initially appear dangerous. Only detailed follow-up on a case-by-case basis can prove each new discovery to be non-threatening. This process must be communicated more carefully, scientists agreed, in the manner that hurricanes are tracked by the weather service until the “all-clear” is announced.

The workshop was attended by 70 scientists from the United States, Australia, Europe and Japan. It was co-sponsored by Ball Aerospace, Science Applications International Corp., Lockheed Martin Corp., the National Optical Astronomy Observatory and the University of Maryland. A formal report on the workshop will be submitted to NASA by the end of 2002.

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SIZES AND STRUCTURES OF COMETS AND ASTEROIDS: WHAT IS WORTH MITIGATING, AND HOW?

Erik Asphaug, Earth Sciences Dept., University of California, Santa Cruz CA 95064 USA asphaug@es.ucsc.edu

Once every 20,000 years, a huge rock mass slams into an ocean basin with little or no warning, generating a tsunami with wave energy equivalent to ~3 gigatons of TNT. Hundred meter high waves propagate across the impacted ocean basin, obliterating coastal cities in their wake. Hundreds of millions of lives are lost, and the cost in purely economic damage is in the trillions of dollars. Yet we do almost nothing about it.

I am talking about volcanic island landslides. Waves spawned by once-per-20,000 year collapses of volcanic mountain flanks (Cumbre Vieja, Kilauea, etc.) are about the same wave energy as would be spawned by a 600 m diameter asteroid (S. Day, pers. comm. 2002). Interestingly, 20,000 years is also about the mean recurrence interval for 600 m NEO impacts. Smaller island collapses (e.g. Ritter Island, 1888) are certainly more frequent than Tunguska-type airbursts, and probably cause at least as much potential harm. And the largest volcanic events, such as the Siberian flood basalts which may have conspired to end the Permian, are about as rare and evidently as deadly as the largest impact events in the present solar system.

These numbers are all quite rough, and the parallels not entirely satisfactory (for instance, asteroids can hit suddenly and anywhere). But it helps objectively constrain our concern with NEOs. They do represent the one potentially catastrophic natural disaster that we think we can mitigate, yet mitigation has its own costs and risks, and if those costs overwhelm the costs of the underlying fundamental research, and if those risks outweigh the hazard they are aiming to subdue, there is little point. At some small diameter, we all agree, mitigation is not worth the trouble. What size is that? In my talk I hope to address this with some precision, or at least with some geophysical motivation.

Any proposed mitigation scenario will be enormously expensive to develop; $10G (~15% the cost of Space Station) is probably a fair estimate of the cost to deflect or disrupt a 300 m diameter NEO with appropriate lead time. In comparison, ~3% of this amount would support a Discovery-class telescope interior to Earth (orbiting at Venus L2, say) capable of telling us with near certainty in two decades that nothing out there larger than 300 m is going to hit us before the next century. Of course, we face a ~1/500 chance of learning bad news instead of good from such a survey – i.e. that we need to prepare for a 300 m impact before 2100 – but then we'll know. From a purely fiscal perspective, it makes 500/3% = 20,000 times more sense to pursue advanced reconnaissance of NEAs, than to pursue any engineered mitigation solution before its time. Reconnaissance is such an enormous bargain that any money spent elsewhere, if taken from the same pool of funds, is folly. This argues strongly for putting the NEO search in a protected budget, so that it does not compete with vastly more expensive, and in the end probably unnecessary, initiatives related to hazardous NEOs.

Yet we must speculate "what if 2002 NT7 was headed our way in 2019". Thermonuclear asteroid mitigation – perhaps our only hope, *today*, in that one-in-a-million dire circumstance – can easily be developed alongside existing weapons testing and development programs. Indeed, research in this area can be continued, and even promoted, in a manner that *affirms* Article IV of the Outer Space Treaty (prohibiting weapons in space) and which affirms the present Comprehensive Test Ban Treaty. Thermonuclear weapons design is done in the modern era by computer modeling, coupled with field- and lab-testing of individual deployable components in a manner that does not yield an explosion. Of particular relevance is the United States Department of Energy Accelerated Strategic Computing Initiative which oversees modeling efforts using the world's fastest supercomputers to perform high-fidelity simulations running advanced 3D thermophysical and nuclear reaction codes.

DoE-ASCI is a well-established and well-funded research program that is already perfectly suited to oversee model development and testing of any thermonuclear asteroid mitigation scenario, alongside the DoE's banner goal to "*shift promptly from nuclear test-based methods to compute-based methods*" (see http://www.lanl.gov/projects/asci).

Of course, blowing up asteroids with weapons of mass destruction is a last resort and would be an emblem of our ignorance – the above is not a responsible plan for the long term human future. The far more likely scenario is that we shall detect all significantly hazardous bodies soon enough, and learn how to divert them in a controlled manner. One need not be branded a blind optimist to presume that advanced and benign, perhaps even profitable technologies for NEO mitigation shall be developed in the coming centuries, so that thermonuclear asteroid mitigation never happens. In the year 25,000 – the average time between now and the next 300 m asteroid strike – we will presumably have better tools. But in the interim it is a rational safeguard to learn the detailed effects of high energy explosions on asteroids by combining existing models for asteroid impact disruption with existing national security computations related to weapons performance.

But any model is only as good as its boundary conditions, and any mitigation modeling program would have to be complemented by extensive field reconnaissance of asteroids and comets. Which brings us back to the scientific requirements that are the subject of this conference: how do we adequately characterize an asteroid's geology.

Rational NEO mitigation priorities are therefore approximately as follows: (1) Link NEO impact predictions to existing warning centers, as this can be done at almost zero cost immediately (e.g. http://www.prh.noaa.gov/pr/ptwc/aboutptwc.htm). (2) Complete the NEO catalog down to about 300 m, for about $300M, within about 30 years. (3) Determine detailed geological characteristics, for a wide range of comets and asteroids, down to sizes of a few 100 m. The latter folds in superbly with the goals of solar system exploration, especially since we now know that NEOs are objects from the main belt and beyond, delivered to our doorstep for free.

These priorities alone are going to represent an uphill but worthy battle for tax dollars. Going another step – trying to deploy intervention mitigation at this time, beyond the conceptual stage – will be a dramatically unsound investment until these first three steps are complete, and may in fact hinder their timely completion by competing for funds. Moreover, and perhaps most seriously, it may elicit a suspicion regarding the honest goals of planetary science, if comparable plans are not also laid out for volcanologists to mitigate the impending collapse of Cumbre Vieja.

LANDER AND PENETRATOR SCIENCE AT NEOS. A. J. Ball, Planetary and Space Sciences Research Institute, The Open University, Walton Hall, Milton Keynes MK7 6AA, U.K. Email: a.j.ball@open.ac.uk.

Introduction: Some investigations of the surface or sub-surface of Near-Earth Objects that are needed to support mitigation demand contact with the surface. Based on discussions at the workshop, the main examples are:

- Seismic tomography, requiring both sources and receivers, to examine the internal structure of NEOs and look for cracks and voids that may influence the mitigation strategy and its effects.
- Surface and sub-surface mechanical properties measurements, to determine the material's response to drilling, digging, hammering, impacts, explosive detonations, etc. The type of measurements performed would depend on the mechanical interaction involved in the mitigation strategy being pursued.
- Measurements of sub-surface thermal properties and volatile content, with a view to using non-gravitational forces (outgassing) for mitigation.
- Emplacement of a radio beacon to help refine predictions of a NEO's orbit.

There are of course many other potential investigations requiring surface contact that appear to be rather less important for mitigation, being motivated wholly by science. Examples include:

- Sub-surface sample acquisition
- Contact or close-up compositional measurements
- Microscopic or sub-surface imaging
- Other *in situ* physical properties measurements, for example some electromagnetic techniques such as complex permittivity and magnetic susceptibility measurements.

Discussion of these thus falls outside the scope of this abstract. However, as concepts for mitigation develop, it is possible that additional requirements for surface or sub-surface investigation will emerge. It is also possible that scientific and mitigation-related investigations will be combined in a single mission.

Of the many concepts for 'surface missions', this abstract focuses on 'payload delivery' penetrators, soft landers, and surface and sub-surface mobility, with particular reference to the four main mitigation-related investigations listed above. Mission objectives may of course be best achieved by other, possibly simpler, means, as illustrated by many previous missions and proposals (examples in brackets):

- Destructive impact of spacecraft for study of the resulting crater or ejecta, or to act as a seismic source (Apollo [1], Lunar Prospector [2], Deep Impact [3], BepiColombo [4], Clementine 2, Don Quijote)
- Passive projectiles, for the same reasons as above or to act as target markers or reflectors (MUSES-C [5,6], Aladdin [7])
- 'Touch-and-go' measurements, e.g. for surface sampling (HERA [8])
- Tethering / anchoring to secure a spacecraft at a particular location (Phobos DAS, Rosetta Lander [9], ST-4 Champollion [10])
- End-of-mission landings for descent imagery and possible extended mission operations on the surface (NEAR [11])
- Hovering at very low altitude (<100 m), for remote investigation of the surface (active or passive); low surface gravity means that minor body surface missions do not necessarily require landing! (Phobos 1 & 2 [12], MUSES-C [13])

Seismic Tomography: This technique has been developed for terrestrial applications [14] and is analogous to what might be performed to study the interior of a NEO (being complementary to gravity field measurements and penetrating radar, which would probably be done in parallel by an orbiting spacecraft) [15]. At least one commercially-available three-dimensional tomographics technique (3dT) can probe sub-surface structures and look up to 150 m ahead of tunnel faces. Transducers for the transmission and detection of seismic signals are placed at a number of locations across the surface or within a series of boreholes. Data received from the detectors (large quantities by spacecraft standards) is then inverted using 'ray paths' (state-of-the-art software) and converted into 3D images. Low seismic velocities represent cavities or low density material, while high velocities represent strong, dense material.

At least three seismic stations would be required (ideally several more). Since they could presumably be distributed across an object's surface to provide ray paths through its deep interior, boreholes would not be necessary, although the stations may need to penetrate a layer of regolith to be sufficiently coupled to the material.

Possible seismic sources include the impact of other stations of the network as they arrive, the hammering of 'mole' penetration mechanisms (that may be employed to achieve deeper penetration and better coupling) and end-of-life explosive detonation of other stations, as well as more conventional transducers.

Inversion of the seismic data would require knowledge of the object's shape and the location of each station, as well as precise timing information on the source impulses. Station orientation information would not be required if compressive, 'P' waves alone are used (as opposed to transverse, 'S' waves).

Mechanical Properties: Measurements of mechanical properties may be necessary to understand the response of the object's materials to particular operations involved in mitigation. The best approach may be to perform essentially the same operation as might be done on a threatening NEO, thus avoiding uncertainties arising from the choice of a predictive model and the assumptions made.

Some basic constraints on mechanical properties (on scales from global to microscopic) may be gained from interpretation of remote measurements (from Earth-based telescopes as well as spacecraft), modelling, laboratory simulations, analysis of meteoritic materials and from the seismic tomography experiment described above. These may be sufficient for the purposes of mitigation, so while dedicated instrument mechanisms optimised for mechanical measurements are conceivable, it may be more efficient to simply perform operations similar to those envisaged and monitor the appropriate parameters. Predictions can then be made for comparable cases.

Soil mechanics properties may vary widely over the surface of a NEO (as suggested by NEAR's imagery of Eros), and between different NEOs, so a thorough assessment of such properties would require visits to multiple locations on multiple objects. In addition, as much contextual information as possible should be obtained at the same locations. This would help us understand what features affect the mechanical properties at a particular location—otherwise one is restricted to a purely statistical approach.

Linking mechanical properties to other features observable remotely (e.g. thermal, optical, radar) via appropriate models of the material's microstructure and surface processes—and obtaining 'ground truth' verification of these links—seems worth pursuing if remotely-sensed maps of predicted mechanical properties are required, e.g. to select an appropriate landing site. This suggests a requirement for a series of instrumented mobile devices to make a standard set of mechanical and other measurements at a series of locations across the surface. 'Hoppers' such as those built for the Phobos 2 and MUSES-C missions—PrOP-F [16] and MINERVA [17] respectively—seem particularly suited to this approach. Indeed, PrOP-F carried a penetrometer and other sensors to carry out a sequence of mechanical, thermal and electromagnetic measurements at each landing site [18].

Some useful soil mechanics information can be gained by careful measurement of any dynamic operations such as landing, impact penetration, anchoring, drilling, hammering and 'touch-and-go' procedures. Sensors to measure force, torque, acceleration, velocity or displacement can be used to extract information on strength properties, texture and layering. An example is the ANC-M accelerometer of the MUPUS experiment mounted in the harpoon anchor of the Rosetta Lander [19]. Interpretation of such data can be difficult, however, since the operation monitored is unlikely to be optimised for scientific measurements (e.g. the geometry may be complex). Another issue for impact accelerometry measurements is the high sampling rate required to achieve good spatial resolution at high impact speeds.

Self-inserting 'moles' have the potential to measure a profile of mechanical and other properties as they advance through the host material, however like many techniques the properties of interest can be disturbed by the instrumentation, requiring modelling and careful experiment design and data analysis. An instrumented mole has been suggested for measurement of the heat flow and regolith properties on Mercury [20].

A further point worth highlighting is that mechanical measurements performed in the low surface gravity environment of NEOs may generate reactive forces or torques that must be balanced (e.g. by anchoring) to avoid ejecting the vehicle from the surface. Moles require an initial insertion force until they start to grip.

Sub-surface Thermal Properties and Volatile Content: In order to predict the effect of heating on the material of a NEO (e.g. by concentrated sunlight) and the prospects for producing useful non-gravitational forces from outgassing, it is necessary to know something about its thermal properties. For example, how effectively could heat be transported from the surface to deeper layers where volatiles (e.g. water ice) may be present?

The measurement of sub-surface thermal properties—temperature profile and thermal conductivity (or, more easily, diffusivity)—can be achieved at a particular location by means of a string of heatable thermal sensors such as the PEN thermal probe of the MUPUS experiment on the Rosetta Lander [21] or the mole- and tether-based sensors proposed for heat flow measurement on the surface of Mercury [20]. The MUPUS PEN probe is a 10 mm-diameter composite tube incorporating a 32 cm-long Kapton sheet, onto which 16 titanium heatable thermal sensors have been laser-sputtered. The thermal probe will be deployed to a distance of ~1 m from the lander (away from its shadow) and hammered into the cometary surface by means of an electromechanical hammering mechanism.

The sensors are used to measure the temperature profile, however the probe itself unavoidably creates a thermal 'short circuit' that must be corrected for by modelling. Heating individual sensors and monitoring the resultant rise in temperature over time enables the local thermal diffusivity to be measured. Heating a long line of such sensors would approximate the line heat source technique for thermal conductivity measurement. Measurements of other physical properties including bulk density and penetration resistance are important in the analysis of such thermal data.

Thermal measurements can also be used to deduce the presence of volatiles, via their effect on the thermal conductivity and energy balance. Heat from thermal sensors can cause volatiles such as water ice to sublimate, increasing the thermal conductivity of the material far beyond that of the 'dry' material. It is also possible to distinguish between volatile species (e.g. between water ice and CO_2) by virtue of their different sublimation temperatures.

Radio Beacon: If a NEO is predicted to undergo a close planetary encounter that could divert it onto a collision course with the Earth, its predicted future orbit will be extremely sensitive to the parameters of the close approach. To assess whether or not the NEO will pass through the 'keyhole' putting it on a collision course thus requires extremely accurate knowledge of its current orbit. One way to achieve this is to fix a radio beacon to the NEO to transmit a stable radio signal that can be used for range and Doppler tracking by ground stations, in the same way as for interplanetary spacecraft.

Delivery of a long-lived station to the surface and anchoring it there to transmit a tracking signal over an extended period of time would thus be required. A similar experiment was planned for the fixed landers of the Phobos 1 & 2 missions [12].

Payload Delivery Penetrators: These are bullet-shaped vehicles designed to penetrate a surface to emplace experiments at some depth. The basic technology for these has existed for several decades [22,23,24], however only in the mid-1990s did proposals for their use begin to be adopted for actual flight.

Impact speeds range from about 60 to 300 m s^{-1}, depending on factors such as the desired depth, the mass and geometry of the device, the expected surface mechanical properties, the shock-resistance of internal components, and constraints imposed by the entry and descent from orbit or interplanetary trajectory. Additional impact damping may be included in the form of crushable material (e.g. honeycomb or solid rocket motor casing), sacrificial 'cavitator' spikes protruding ahead of the penetrator's tip (e.g. Luna-Glob high-speed penetrators, with speeds exceeding 1.5 km s^{-1}) and gas-filled cavities (e.g. Mars 96 penetrators).

Masses have ranged from the tiny DS-2 Mars Microprobes at 2.5 kg each (excluding aeroshell) to 45 kg each for the Mars 96 penetrators (4.5 kg payload).

Penetrators may consist of a single unit, or a slender forebody and a wider aftbody linked by an umbilical tether, the two parts separating during penetration to leave the aftbody at the surface. Expected forebody penetration depths have ranged from ~0.5 m for the Mars Microprobes (impacting at ~190 m s^{-1}) up to 4-6 m for Mars 96, with 1-3 m expected for the single-body Lunar-A penetrators (13 kg each, 140 mm diameter, impacting at ~285 m s^{-1}). Power is provided by batteries or RTGs. The DS-2 Mars Microprobes' nominal lifetime was only a few hours, while the Lunar-A penetrators are expected to have enough power for about a year. Transmission of data back to Earth is usually by means of an omnidirectional antenna and a relay spacecraft.

Experiments flown on (or proposed for) penetrators include the following:

- Accelerometry / gravimetry / tiltmeter
- Thermal sensors (temperature profile, thermal conductivity / diffusivity, heat flow)
- Imaging
- Magnetometer
- Permittivity / conductivity sensors
- Seismometer
- Spectrometers (γ ray, neutron, α / proton / X-ray, X-ray fluorescence, etc.)
- Sample collection for evolved gas analyser / spectroscopic analysis
- Penetrators with combined sampling and pyrotechnic return
- Explosive charge
- Meteorological sensors (not applicable to atmosphereless bodies such as NEOs of course!)

Many of the penetrators flown or proposed have technological features that may be applicable to NEO missions. These include propulsion for braking or acceleration, attitude control, low-temperature shock-resistant components, miniaturisation, and experiments for seismology, thermal and mechanical properties and water ice detection. Sadly, neither the Mars 96 penetrators nor the DS-2 Mars Microprobes completed their missions—Lunar-A now has the task of demonstrating penetrator technology on another world for the first time. The following list gives key references for penetrator missions and proposals:

- Mars 96 Penetrators [25]
- DS-2 Mars Microprobes [26,27]
- Lunar-A Penetrators [28]

- Vesta / Mars-Aster Penetrators [29,30]
- CRAF / Comet Nucleus Penetrator [32]
- BepiColombo Mercury Surface Element—Penetrator Option [31] and Hard Lander/Penetrator Option [33]
- Luna-Glob High-Speed Penetrators [34,35] and Large Penetrators / Polar Station [36,37]

Soft Landers and Mobility: The first soft landers for asteroid-like worlds were those of the Phobos 1 & 2 missions. Both spacecraft carried a fixed lander (the DAS, or Long-term Autonomous Station), while Phobos 2 also carried a mobile lander or 'hopper' (PrOP-F) [16]. Sadly, both missions were lost before either type of lander was deployed.

The payload of the Phobos DAS comprised TV cameras, the ALPHA-X spectrometer, the LIBRATION optical sun sensor, a seismometer, the RAZREZ harpoon anchor penetrometer and a celestial mechanics experiment. The lander would have anchored itself to the surface and deployed solar arrays, and was expected to survive for several months.

PrOP-F was 0.5 m in diameter, had a mass of 50 kg including a 7 kg payload. Measurements were to be made at several locations within ~1 km of the initial landing site, spending 20 min at each site. The near-spherical lander had four 'whiskers' to turn itself back onto its circular base after each landing, in order to bring its sensors and foot-like hopping mechanism into contact with the surface. Power from the batteries was expected to last at least 4 hours. PrOP-F's payload was as follows: ARS-FP alpha-X-ray spectrometer, magnetometer, Kappameter magnetic permeability / susceptibility sensor, gravimeter, temperature sensors, conductometer, and mechanical sensors (incl. penetrometer).

The Japanese mission MUSES-C, as well as hovering close to the surface of its target asteroid and gently touching the surface to acquire samples, will also carry a 'hopper' called MINERVA, much smaller than PrOP-F with a mass of 0.55 kg [17]. Its payload comprises 3 CCD cameras, thermal sensors, mechanical sensors and sun sensors. It will draw power from solar cells and has an internal motor-driven rotary hopping mechanism that is able to provide some degree of directional control for the hopping. Also planned for MUSES-C but later cancelled was NASA's MUSES-CN nanorover. Its planned payload comprised a multi-band camera, a near-IR point reflectance spectrometer, an APX spectrometer and a laser ranging system. The problem of mobility on minor bodies is addressed by reference [38]. New concepts for minor body surface mobility include the three-legged 'rock crawler' from ISAS.

The idea of self-inserting 'moles' to deploy experiments underground or acquire samples has been around for many years in various forms, e.g. [39], but only recently has a mole been adopted for actual flight, in this case for sub-surface sample acquisition on Mars [40]. Other types of mole have been proposed, for example the Inchworm Deep Drilling System concept [41]. The mole-based experiment for heat flow and regolith properties measurements on Mercury [20] illustrates some of the potential for integrating a suite of sensors into a mole for *in situ* experiments.

The cometary mission Rosetta includes a 90 kg lander with a 26 kg payload designed to carry out a wide range of investigations on the nucleus of comet 46P/Wirtanen, including imaging, sample analysis and physical properties measurements [42]. On touchdown the Rosetta Lander will anchor itself to the surface; the 10 payload experiments include several that might be adaptable for use in mitigation studies on NEOs. These include MUPUS (thermal and mechanical properties of surface and sub-surface material), CONSERT (radio tomography of the nucleus interior), SESAME (including CASSE sensors for measurements of the acoustic properties of the near-surface layers) and SD2 (sampling drill).

Technology developed for NASA's cancelled ST-4 Champollion mission might also be adapted for use in mitigation studies on NEOs, including the Comet Physical Properties Package (CPPP) and the pyrotechnically-driven telescopic anchoring spike [10].

Discussion: NEO mitigation studies by surface missions are likely to include seismic tomography and measurements of mechanical and thermal properties and volatile content. Such experiments should be performed on a set of example objects reflecting the diversity of the NEO population. There is choice of surface mission architectures to achieve such goals, namely:

- Single fixed surface station—good for detailed composition measurements by on-board sample analysis
- Mobile surface station—good for coverage of surface properties at varied locations
- Network of surface stations—good for tomography as well as coverage

Of these, the scientific requirements of surface-based NEO mitigation studies seem best served by a network of fixed surface stations, possibly supplemented by a mobile surface element for improved coverage of particular properties, and/or the capability for sub-surface mobility (perhaps a penetrator forebody that is also a mole?).

Fixed soft landers may need anchoring, of course—indeed this is essential on fast-rotating NEOs. Surface mobility would appear difficult for such bodies—perhaps this is an area for future investigation? A requirement for anchoring immediately implies a need for some form of attitude control, to ensure correct deployment of the anchoring system.

The likely requirements for anchoring, good seismic coupling, and sub-surface measurements of mechanical and thermal properties and volatile content all point towards penetrators rather than soft landers as the appropriate vehicles for surface-based NEO mitigation studies.

The low escape velocity of NEOs means that a penetrator's impact speed has to be achieved either by on-board propulsion—resulting in extra mass and complexity—or with the arrival speed of the carrier spacecraft. A high-speed flyby scenario would seem to be ruled out, given the resulting short duration window for data relay and other measurements, as well as the possible need to perform initial mapping of the NEO to enable impact site selection. A separate spacecraft sent to rendezvous with the NEO could perform these functions, however. On the other hand, if the required penetrator impact speeds are not much larger than 60 m s^{-1}, the carrier could arrive at such a relative speed, deploy its salvo of penetrators and then fire its thrusters to achieve rendezvous.

Practical considerations for penetrators include the availability of ground test facilities capable of accommodating the appropriate impact speed, projectile mass and diameter and representative targets. Simulation tools are clearly important, given the cost of impact tests. All system and payload components must have sufficient shock resistance, and shear forces must be considered as well as axial loads, an issue related to the provision of attitude control of the penetrator.

In summary, investigations related to NEO mitigation will require surface and sub-surface instrumentation where other means cannot meet the requirements. Many of the component technologies exist already but technological development and mission studies are currently needed in a number of areas.

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UNDERSTANDING THE DISTRIBUTION OF NEAR-EARTH OBJECTS. W. F. Bottke, *Southwest Research Institute, Boulder, CO 80302, USA, (bottke@boulder.swri.edu)*, A. Morbidelli, *Observatoire de la Cote d'Azur, Nice, France*, R. Jedicke, *Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721.*

The orbital and absolute magnitude distribution of the Near-Earth Objects (NEOs) is difficult to compute, partly because known NEOs are biased by complicated observational selection effects but also because only a modest fraction of the entire NEO population has been discovered so far. To circumvent these problems, we have used numerical integration results and observational biases calculations to create a model of the NEO population that could be fit to known NEOs discovered or accidentally rediscovered by Spacewatch. This method not only yields the debiased orbital and absolute magnitude distributions for the NEO population with semimajor axis $a < 7.4$ AU but also the relative importance of each NEO replenishment source.

We list a few of our key findings here, with a full accounting given in Bottke et al. (2002a, Icarus 156, 399). Our best-fit model is consistent with 960 ± 120 NEOs having absolute magnitude $H < 18$ and $a < 7.4$ AU, with approximately 55% found so far. Our computed NEO orbital distribution, which is valid for bodies as faint as $H < 22$, indicates that the Amor, Apollo, and Aten populations contain 32±1%, 62±1%, and 6±1% of the NEO population, respectively. We estimate that the population of objects completely inside Earth's orbit (IEOs) arising from our NEO source regions is 2% the size of the NEO population. Overall, our model predicts that 37 ± 8%, $25 \pm a3$%, 23 ± 9%, 8 ± 1%, and 6 ± 4% comes from the ν_6 resonance, the intermediate-source Mars Crossing (IMC) region (i.e., a population of Mars-crossing asteroids with perihelion $q > 1.3$ AU located adjacent to the main belt), the 3:1 resonance, the outer main belt, and the Jupiter-family comet region, respectively. The influx rates from the main belt needed to keep the NEO population in steady-state is 790 ± 200 objects per Myr. 72% of these objects come from the outer main belt, where chaotic diffusion of objects is strong. We also estimate that there are 60 ± 51 extinct comets with $H < 18$ in the JFC-NEO region. This value corresponds to 200 ± 160 km-sized comets in the JFC region, with 78% of them being extinct comets.

Applying the results of this model, our team has also developed a method for determining the debiased albedo/orbital distribution of the NEOs (Morbidelli et al., 2002, Icarus 158, 329.). Our work shows that an observationally complete NEO population with diameter $D > 0.5$ km should contain 53% bright objects (e.g., S-type asteroids like 433 Eros) and 47% dark objects (e.g., C-type asteroids like 253 Mathilde). By combining our orbital distribution model with our albedo distribution model, and assuming that the density of bright and dark NEOs is 2.7 and 1.3 g cm^{-3}, respectively, we estimate that the Earth should undergo a 1000 megaton (MT) collision every 64,000 years. On average, the bodies capable of producing 1000 MT blasts are those with $H < 20.5$; only 18% of them have been found so far.

We have also combined our debiased NEO population results with a survey simulator in order to investigate the time needed by existing NEO surveys to find 90% of the NEOs larger than 1 km diameter. In our most realistic survey simulations, we have modeled the performance of the LINEAR survey over the 1999-2000 (inclusive) period (Jedicke et al. 2002, Icarus, in press.). Tests indicate that our survey simulator does a reasonable job at reproducing LINEAR's NEO detections over this time frame. For this reason, we have some confidence that extending our simulator results into the future will also produce realistic results.

Our results indicate that existing surveys (as of January 2001) will take another 33 ± 5 years to reach 90% completeness for $D > 1$ km asteroids. Our predicted timescale to reach the Spaceguard goal is longer than other recent estimates because our undiscovered NEOs have a very different orbital distribution than our discovered NEOs. Conversely, advances in survey technology over the last 6-12 months have allowed LINEAR to improve their limiting magnitude (J. Evans, personal communication), such that they can now find fainter objects than they could as of January 2001. We are still investigating the implications of their changes (and improvements made to other NEO surveys), but our test results suggest that the Spaceguard goal could be achieved as soon as 2014, better than the 2035 estimate given above. We believe this issue will need to be continually revisited over the next several years as surveys get better at finding NEOs.

We have not yet attempted a cost-benefit analysis, but our results suggest that a local-area network of telescopes capable of covering much of the sky in a month to limiting magnitude $V \sim 21.5$ may be administratively, financially, and scientifically the best compromise for reaching 90% completion of NEOs larger than 1 km diameter by 2008. We find that distributing survey telescopes in longitude/latitude may produce a 25% savings in the time needed to reach the Spaceguard goal. This value can be used to assess the relative merits of a southern hemisphere NEO survey against factors like cost, time needed to reach operational status, etc. Our results also indicate that a space-based satellite survey on an orbit inside Earth orbit (e.g., perihelion near Mercury) would offer significant advantages over terrestrial surveys, such that a Discovery-class mission to discover NEOs might be warranted.

For more information on these topics, please go to:
http://www.obs-nice.fr/morby/ESA/esa.html

IMPACT: AN INTEGRATED APPROACH (Space and Ground) FOR MONITORING THE THREAT OF EARTH ORBIT CROSSING CELESTIAL BODIES

L. Bussolino

Alenia Spazio S.p.A. Strade Antica di Collegno 253
10146 Torino (TO)
E-mail: lbussoli@to.alespazio.it

ABSTRACT

The threat of possible collision of asteroids and comets with our planet has reached an international stage since1990 when U.S.A. Congress set up a dedicated committee for the analysis and the assessment of this problem. The U.N. organized a congress later on to summarize the current knowledge on this subject as well as the European Council recommended its member states to conduct studies to further deepen the understanding in terms of tackling and solving this kind of problem interesting the entire world.
IMPACT is the acronym for " International Monitoring Program for Asteroids and Comets Threats " coming out as proposal from a study funded by the italian region PIEMONTE throughout the Civil Protection Bureau and performed by the Planetology Group of the Astronomical Observatory of Torino (Italy) for the scientific side and Alenia Spazio for the engineering part.
They have carried out a series of analyses aimed at contributing in subsequent steps to the solution of the two fundamental problems associated to the potential impact threat: the assessment of the numbers of killers/terminators and the impact rates from one side and the development of the idea of considering space segments for supporting activities of discovery as well as the physical and mineralogical characterization using satellites in orbit around the Earth.
The present paper will ponder a synthesis of the activities performed during this and other additional studies also funded by the European Space Agency where the space technology appears to offer a great contribution if conveniently integrated with the Earth networks for Potentially Hazardous Asteroids (PHA) detection.

THE THREAT

The highly spectacular collision between comet P/Shoemaker-Levy 9 and Jupiter might be already forgotten, but recently two asteroids such as 2002 MN on June 14th passed at 74.000 miles and 2002 EM7 on March 8th, passed within 288.000 miles of the Earth, have recently brought to the public opinion's attention and highlighted a well known general problem whose practical consequences , however , have never been examined in sufficient detail, namely that the Earth may directly collide with heavenly bodies.
The potential Earth impactors are objects such as asteroids and comets which belong to our Solar System having the orbit passing near to our planet or crossing its orbit ; for this reason In the literature they are known as N.E.O. (Near Earth Object) as well as E.C.A. (Earth Crossing Asteroid).
Scientists and astronomers supported by numerous enthusiast private amateurs are making surveys of the sky for detecting those objects and studying NEO characteristics ; some of them have been discovered and analyzed but the common understanding is that the discoveries are still far from the preliminary estimate done by scientists as E. Shoemaker, E.J.Opik and many others.
Only one third of the 1 km diameter class asteroid is well known.
The close call of June 14th with the football-field sized asteroid is important because of the

risk associated to the mass non negligible (diameter within 50 and 120 meters) or 70-100 meters, following other source, and the estimated velocity of 23.000 miles per hour and for the fact that we did not even see it, it had passed us only three days after.
Worries about an asteroid collision with Earth have grown in part because a better detection net has revealed how many close calls our planet has had. In any case both the 2002 MN and the previous 2002 EM7, that passed within 288.000 miles of Earth, came from "blind spot" near the sun and have not been detected until several days after they passed.
Many scientist are oriented to the discovery of these objects because very few of them have been discovered.
Some other scientists are focusing their attention on the assessment of the potential damage coming from an impact of the asteroid or the comet with the Earth. In this case is of extreme importance define the dimensions of the celestial body , the orbit and the velocity along the orbit and the chemical/mineralogical composition for computing the impact energy and the related release methodology. Having understood that the impact energy is very important and of the order of thousands megatons equivalent is coming important " to characterize " the object, defining size, inertial characteristics and average density.
For the above reason it is important to discover the NEO from 1 km in diameter and above (because to them is connected a cataclysm that will terminate the life on the Earth surface) but is important in any case investigate the celestial bodies of 0.5 km because they are not less hazardous and also the 100 m in diameter because they could kill millions of persons and destroy entire cities and surroundings.
Then the problem focusing the attention of many scientists has to be how to detect and study the NEO.

A SPACE SEGMENT FOR MONITORING THIS THREAT

The main consideration for using space and then satellites in orbit is coming directly from the scientists themselves that are requiring time for observation in the major institutes, where sun and the other planets are observed with priority. The apparent solution would be to build up other telescopes specifically utilized for the NEO discovery , follow-up and characterization.
The second point is also given by the scientists complaining for the scarce possibility of observation in relationships with the weather conditions, light pollution and atmospheric absorption for observation in the visible as well as in the infrared wavelengths.
A telescope in orbit around the Earth such as the Hubble Space Telescope working orbit in the visible or as IRAS and ISO with infrared telescope, thermally controlled in a specific dewar , are example of what can be obtained, even if the cost is well higher than a ground based telescope.
The availability in terms of operability of the satellite is full for the whole day for the period of on orbit lifetime , that might be ranging from two to five years without any interruption. The orbital position is also offering additional features as well as the possibility to observe specific objects near to the sun that cannot be detected by ground observatories.
The period of time necessary for detecting all the asteroids is of the order of twenty/thirty years considering the number of 1500/1600 bodies and the rate of discovery of LINEAR organization at level of forty per year , excluding the celestial bodies of medium /long period that appear every fifteen or more years. The same results can be obtained in orbit in a shorter period of time, in relationships with potential threat represented by the fact that till now only one third of the asteroids are known.

IMPACT AS INTEGRATED SYSTEM FOR THE NEO MONITORING

The first line of defense is the ability to discover the NEOs, to compute their orbital parameters and to simulate their evolution with time; this allows forecasting possible perturbations to their orbits, usually arising from close encounters with the major planets, and the resulting trajectory disruptions which may eventually lead to collisions with the Earth.
As repeatedly stressed, in order to better assess the hazards associated with possible collisions between the Earth and the NEOs, their physical and chemical characterization is as important as their discovery.
One way to improve the precautionary measures in response to the NEO threat is definitely the possibility to improve the above mentioned activities as well as the various tools of discovery, namely at least six ground based, 2 m telescopes capable of spotting object with magnitude 22-24, corresponding to about 100 m

Impactor diameter.
As pointed out in the previous chapter, the use of artificial satellites may extensively support and complement the ground-based instruments, thereby enhancing the overall discovery and monitoring capabilities. A well coordinated network including mission control, spacecraft management and data analysis centers may well be a stable, viable structure with both a space and a ground segment and would be able to meet the protection and security requirements. This is precisely the approach Alenia Aerospazio has studied and developed. Where as:

• the asteroid impact hazard is a global issue and the actions undertaken to tackle it require a broad participation towards a common goal;
• NEO discovery, continuous monitoring and follow-up characterization costs are high and can best be shared at the international level by exploiting different sinergies;
• active defense research and testing are delicate issues and are best accepted if widely included in the framework of a common goal with worldwide participation.

Astronomical Observatory of Torino and Alenia Aerospazio have proposed the "IMPACT" project, for International Monitoring Program for Asteroid and Comet Threats, aimed at developing a world-wide system to protect the Earth from the NEO/ECA/ECC hazard. The IMPACT system envisages the following main elements:

• the Scientific Center, i.e. the hub of the system, where the main command, control, data collection and analysis, data archiving and distribution functions are carried out;
• a set of ground stations which receive the scientific and housekeeping data from various satellites and from the STONE (for Satellite To Observe Near Earth) satellite;
• a set of specialized centers (NSF, for NEO Study Facilities) supplying specific services such as local data archiving and distribution;
• the STONE satellite or other Earth-orbiting satellites which observe the sky and return their data to the ground;
• external institutions, such as the Public Safety Protection Offices of various countries and professional and amateur astronomer centers, which make use of the data and services generated by the IMPACT system.

The IMPACT system would meet Civil Protection requirements for hazard forecasting, throughout asteroid identification and characterization, impact timing and effect assessments, and population type, density and economy data integration, thereby allowing alert plans to be prepared to reduce the consequences of a possible impact. The system would also ensure support to the surveillance function, i.e. the continuous monitoring of the ongoing events and the evolution of possible criticalities, risk alert and hazard warning.
As far as crisis and crisis aftermath management is concerned, the IMPACT system could only provide its mscientific and communication facilities to support status assessments and co-ordination efforts of pre-existing networks. In fact, to date no active defense is available against NEO impacts, although the day is not far when NEO studies , asteroids characteristics data base will allow our missiles (nuclear as well as not) or other means to be used to protect our planet from the impact hazard.
The system proposed by Alenia Aerospazio will take maximum advantage of the experience of our Company in such areas as ground station development, scientific satellite development and Earth observation satellites such as the Cosmo-Skymed network and Envisat.
The system as proposed might be considered as an initial step towards a more sophisticated alert organization with a chain of sentinel satellites around the Earth and /or space stations with scientific equipment and acting as control center or some dedicated platforms, co-orbiting with Space Station and integration devices to be used as countermeasures in case of possible impact.

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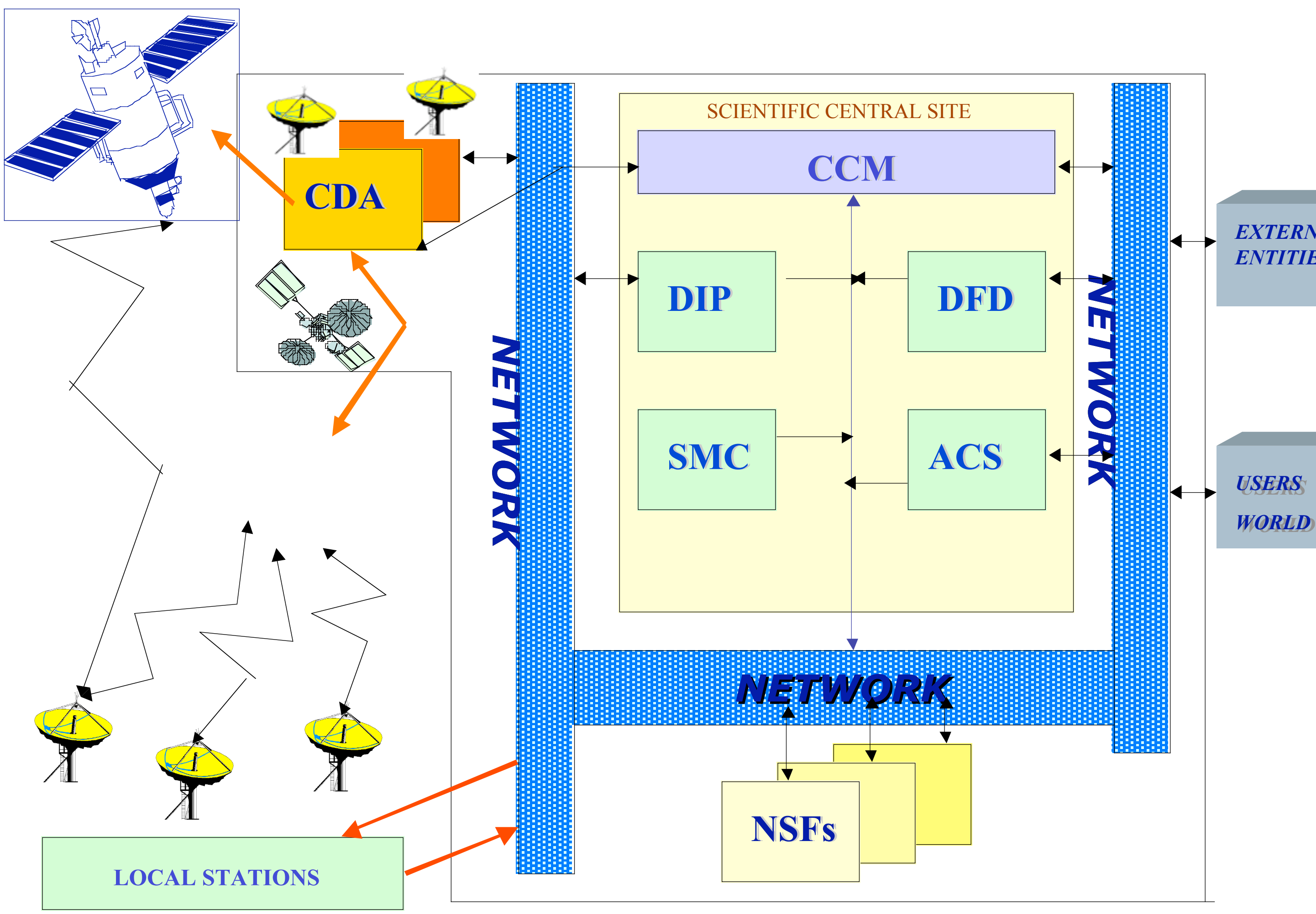
THE SCHEME OF IMPACT NETWORK



PHYSICAL CHARACTERIZATION OF NEOs BY MEANS OF REMOTE OBSERVATIONS FROM SPACE.

A. Cellino[1], M. Delbò[1], K.Muinonen[2], E.F. Tedesco[3], S.D. Price[4], M. Egan[4], M. Ragni[5], L. Bussolino[6]. [1]INAF-Torino Astronomical Observatory, [2]Observatory, University of Helsinki, [3]TerraSystems, Inc., [4]Air Force Research Laboratory, [5]University of Perugia, [6]Alenia Spazio.

Introduction: The general concept of a dedicated space-based observatory for NEO physical characterization and discovery of new objects belonging to orbital classes difficult to observe from the ground (Atens, IEOs) is presented. The purpose of such a mission would be to derive sizes and surface albedos using the radiometric technique, and to discover a large fraction of the existing Atens and IEOs during an operational lifetime of a few years. We are currently conducting a study funded by the European Space Agency to assess the options and do preliminary design and performance trade-off analyses for this kind of mission. Initial results indicate that observations spanning a wavelength interval including the peak thermal emission between 5 and 12 microns, are needed and suitable to attain the scientific goals of the mission. Intrinsic advantages of a space-based platform for reaching the above-mentioned objectives are discussed, as well as the technical problems to be solved, and an assessment of the overall costs. It seems likely that current technology is mature for conceiving a relatively cheap mission, in which most of the temperature requirements are met by means of passive cooling. This can be possible if the spacecraft orbits sufficiently far from the most intense sources of heat. Different orbital options for the satellite are being investigated with the leading candidates being orbits around the L2 Lagrangian points of either the Earth or Venus. Both options present advantages and drawbacks that must be carefully assessed.

NEO Physical Characterization: Physical characterization of NEOs is essential for a better understanding of the properties and histories of these objects, and to develop credible techniques for hazard mitigation. Many of the relevant physical parameters describing the internal structures of NEOs can only be accurately derived from local "in situ" investigations by space probes. For instance, it is widely accepted that one of the most critically missing pieces of information concerns the internal structures of these bodies. Are they mostly consolidated bodies, or are they highly fragmented, porous “rubble piles”? Being able to give a satisfactory answer to the above question is of the highest importance for the development of credible hazard mitigation strategies, and would also imply a huge step forward in our general understanding of NEOs, their likely origin and the histories of their parent bodies. Information about the internal structures of NEOs, however, are difficult to obtain. The only really productive way seems in principle to be direct exploration and *in situ* experiments, implying that dedicated space missions to a forcedly limited sample of objects are strongly needed. There is a wide agreement among the scientific community that this is the best conceivable way for obtaining data crucially needed for the development of reasonable mitigation strategies. However, this does not mean that we are currently in an era in which remote observations are no longer useful. We should take into account two basic facts. First, the NEO population is intrinsically heterogeneous, including objects believed to have experienced very different histories. For instance, the cometary contribution to the NEO population at different sizes is still a controversial subject, although it is generally believed that bodies of asteroidal origin dominate the NEO inventory down to sizes around 1 km. In any case, it is clear that the number of bodies which can be reasonably predicted to be target of rendez-vous missions will be in any case small, and not sufficient to cover the whole range of diversity thought to be present in the NEO population. Second, we should not overemphasize what we really know at present about the physical properties of NEOs. The situation in the field of physical characterization is currently much worse with respect to discovery rate and orbital determination. In a situation in which even a reliable determination of the absolute magnitude of the objects is subject to considerable errors, of the order of 0.5 mag typically, it is clear that it is even more difficult to obtain good determinations of basic physical parameters like the size and the surface albedo. Sizes, for instance, cannot be determined simply by knowledge of the apparent brightness and distance of the objects, because the apparent brightness is strongly dependent on the albedo, which varies over a very wide range among NEOs (between 0.05 and 0.4). Moreover, the quoted uncertainties on the absolute magnitudes also contribute to unacceptably high uncertainties in the size determination. As a matter of fact, sizes and albedos have been measured for only a very minor fraction of the whole sample of known NEOs. The number of objects with a reliably measured albedo is about 50, against a population of more than 2000 objects. This introduces some relevant uncertainties about the predicted inventory and size distribution of the population, and consequently on the impact hazard, which is obviously dependent on the number of potential impactors in different size ranges. Therefore, we are convinced that remote sensing is still, and will remain also in the near future, absolutely necessary to provide valuable information on the distributions of important physical parameters such as size, geometric albedo and spectral reflectance. The most debated problem in this respect is to evaluate what kind of observing facility can best meet the needs of NEO physical characterization. Currently, most physical data about NEOs have been obtained from spectrophotometry and spectroscopy at visible wavelengths. In other words, we know mostly the colors and in some cases the visible spectra of a sample of about 200 objects. This is sufficient to derive a general taxonomic classification of these objects. It should be taken into account, however, that in some cases an ambiguity remains, since there are taxonomic classes, like E,M,P, which cannot be distinguished on the basis of visible colors or spectra, alone. Additional information on the objects' albedo is needed in these cases, but this is rarely known in the case of NEOs. In the case of main belt asteroids, it is known that different taxonomic classes are characterized by different ranges of albedo. In this way, apart from the cases of the E,M,P objects, knowledge of the taxonomic classification can be in principle sufficient to have some estimate of the average albedo of the corresponding objects, and this can be used, knowing at the same time also the absolute magnitude H, to derive reasonable estimates of the sizes. This could also be applied to NEOs in principle, since the determination of colors and/or spectra needed for taxonomic classification can be done using sizeable telescopes. This kind of albedo and size estimate is very indirect, however, and not very precise due to the fact that among the members of any given taxonomic class the corresponding albedo range is often not negligible, leading to intrinsic uncertainties in the resulting size estimates. Moreover, some recent observations of NEOs using the radiometric technique (see below) for the determination of sizes and albedos, has evidenced several cases in which the measured albedo turns out to be very unusual for bodies belonging to some given taxonomic class [1]. This might be due to the fact that NEOs are characterized by different surface properties, being on the average younger and smaller than main belt asteroids of the same taxonomic class. Whatever the reason of these apparent discrepancies, if confirmed by further observations, they would imply in any case that albedos and sizes of NEOs derived from taxonomy are affected by high relative errors. Based on the above considerations, and taking into account that sizes and albedos are very important physical parameters characterizing the objects, we are convinced that highest priority should be given in the near future to the task of obtaining an extensive data-set of *accurate* size and albedo measurements of NEOs by adopting the most suitable observing techniques to reach this goal. This conclusion is also in agreement with some statements and recommendations issued at the end of the Erice Space Chemistry School, July 2001, on "The Physical Properties of Potential Earth Impactors: Know Your Enemy": "*The most crucial datum needed for assessing the NEO hazard is the size of the objects. This information is lacking for the majority of known NEOs and is the highest measurement priority after discovery and orbit determination"*

The Role of Radiometry: Radiometry, spectroscopy, photometry, polarimetry and radar experiments are the most important techniques which can be (and are) used for the purposes of NEO physical characterization. Each technique has its own advantages and drawbacks, needs different instrumentation, and is able to provide different kinds of information. In principle, all the above techniques should be used, since they nicely complement each other. Among them, photometry and spectroscopy must be discarded as primary tools for the determination of sizes and albedos, for the reasons explained above. Among the remaining techniques, thermal radiometry is the most efficient means of gathering data on the sizes and albedoes for significant numbers of NEOs in relatively short times. This is also shown by the fact that the vast majority of data on asteroid sizes and albedos have been collected so far by means of radiometric observations (IRAS and MSX catalogs [2]). Thermal radiometry is based on the fact that both the amount of scattered sunlight from the surface of an object and its thermal emission at IR wavelengths depend on the size and albedo of the body. The situation is complicated by the fact that the thermal emission is also determined by the distribution of the temperature on the object's surface, but it is true that in principle a simultaneous measurement of the visible and thermal IR fluxes from an object leads to the simultaneous determination of its size and albedo, if some reliable model of the thermal properties of the surface is available. The so-called *Standard Thermal Model* (STM) has been successfully applied in the past in the reduction of IRAS data, whereas more recently a new model (NEATM) more specifically suited to the case of NEOs, which are on the average much smaller than the observed main belt asteroids, have likely different regolith properties and are observed over much wider ranges of phase angles (the Sun- object – Earth angle) has been developed and applied to NEO radiometric observations [3]. The main problem of radiometry is that the thermal emission of the objects peaks in the region around 10 μm, where the absorption and emission from the Earth's atmosphere constitutes a major problem for the observations. For this reason, the vast majority of radiometric data for the minor bodies of the solar system has been obtained so far by space-based instruments, like IRAS, MSX and ISO. This is a first important reason to seriously take into account the possibility of developing a NEO-dedicated space-based observatory.

Rationale for a Space-Based Observatory: Some obvious advantages of a space-based instrument with respect to conventional ground-based telescopes are a high duty cycle, the lack of limitations due to the presence of the atmosphere, and a wide sky coverage, including regions of the sky at small heliocentric elongations. The latter, is a fact of primary importance. The reason is that a space-based observatory, in addition to observing known objects in order to measure their sizes and albedos, can in principle more readily detect objects having orbits that are mostly or totally interior to the Earth's orbit. These objects, Atens and IEOs, are difficult to observe from the ground. As a matter of fact, we are still waiting for the discovery of the first IEO, in spite of the fact that these bodies must exist, since integrations of the orbits of known NEOs indicate that during their evolution these objects spend some fractions of time as IEOs [4]. Apart from Atens and IEOs, moreover, it should also be taken into account that simulations carried out recently by Chesley and co-workers, and presented at the Arlington workshop, show that current ground-based searches are not able to discover all the potential impactors hidden in the NEO population, one reason being also that these objects should be detectable in advance mainly in the regions between 90 and 120 degrees from the Sun, where current surveys, including LINEAR, do not observe efficiently. On the basis of all the above considerations, we believe that the development of a dedicated space-based observatory would be well justified by the fact that such facility could perform efficiently two separate tasks, namely the determination of sizes and albedos, and the discovery of objects visible from the Earth at small solar elongation angles. No ground-based observatory can conceivably be built or improved in order to accomplish the same tasks above with the same efficiency as a dedicated satellite. It should also be taken into account a number of other advantages of a space-based telescope working at IR wavelengths. First of all, the size of the telescope could be modest, of the order of 70 cm. The reason is that NEOs are relatively bright at wavelengths around 10 μm. Figure 1, taken from [5], shows as an example the predicted spectral energy distribution for an object 1 km in diameter, observed at opposition at a distance of 2 AU from the Sun (1 AU from the Earth). It is easy to see that NEOs, independently of their taxonomic type, are relatively bright in the thermal IR. At visible wavelengths the reflectance flux is similar to that from a 20 magnitude star, whereas the thermal flux around 10 mm is of the same order of the flux from a 10 magnitude star at the same wavelengths. This means that the stellar background contamination is substantially reduced when observing at thermal IR wavelengths, even at low galactic latitudes.

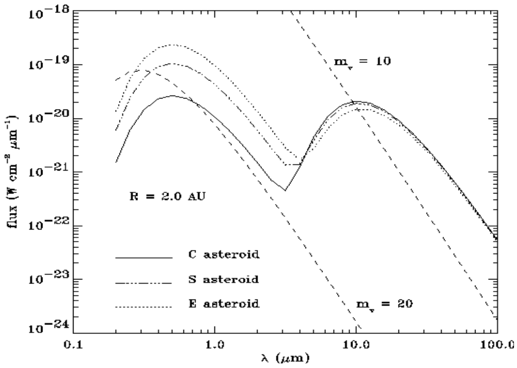


Figure 1

General concept: We are currently working for a general concept of mission, with the support of the European space Agency. The basic idea is to have a low-cost mission which should be an ideal complement of the activities performed from the ground. This could be accomplished by means of a modest-size telescope (60-80 cm in diameter) conveniently located far from the major sources of heat, in order to perform most of the necessary cooling (telescope optics, baffle) passively, without the need of heavy (and expensive) tanks of hydrogen or helium. Only the IR array needs to be cooled to temperatures of the order of 20K by means of active devices, such as inverse Brayton cryocoolers. The IR array should ideally have a cut-off wavelength slightly beyond 10-11 mm. This makes HgCdTe arrays ideal candidates, but other options are also possible and are currently under consideration. Two main options are under scrutiny for the focal plane assembly: (1) a visual + IR option, in which observations are also carried out simultaneously at visible wavelengths by adding a CCD detector. This option would be better in principle for carrying out radiometry, limited spectrophotometry and for astrometric purposes. (2) A purely IR sensor. This option makes sense mainly in the case where another independent satellite is launched to perform near-simultaneous NEO observations at visible wavelengths, thus allowing use of a smaller telescope (not larger than 60 cm) for the IR spacecraft.

Orbital Options: Since the main goals of the mission are the derivation of size and albedo for the largest possible number of known objects, and the detection of the maximum possible number of new Atens and IEOs, we are currently simulating the expected performances for a number of different scenarios. First, since the IR sensor must be located far from the major

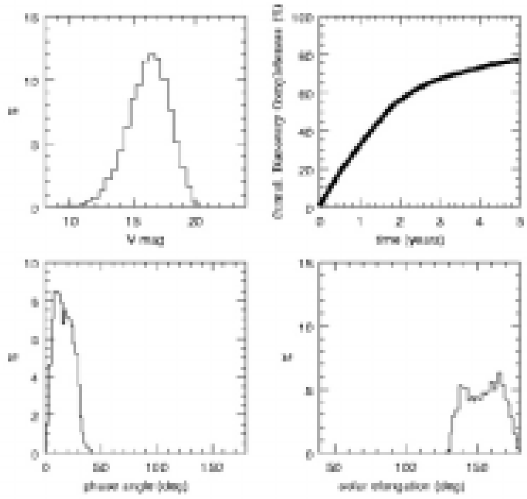


Figure 2. Results of a simulation of observations from L2 of Venus

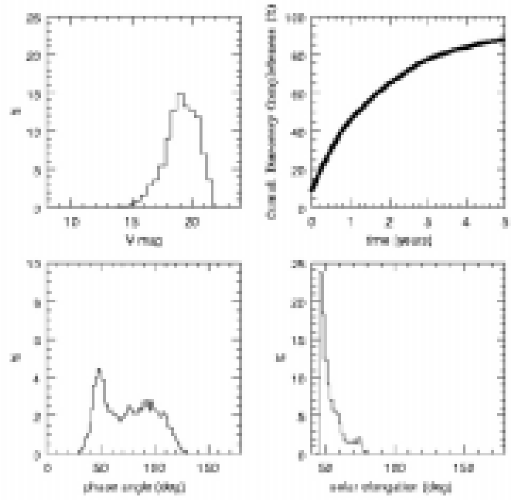


Figure 3. Results of a simulation of observations from L2 of the Earth

heat sources, like the Earth itself, in order to perform efficiently with passive cooling of most of the payload, we are considering orbits librating around the L2 Lagrangian point of both the Sun-Earth and the Sun-Venus systems. Both options have advantages and drawbacks. In the case of the Earth L2 option, the advantages are a cooler thermal environment, a much easier telemetry of the data, and a simpler orbital transfer from the Earth. The drawbacks are the need to systematically observe a region of the sky close to the Sun (typically down to 40 - 50 degrees) to discover Atens and IEOs, the fact that the objects are observed at large phase angles (the Sun - asteroid – spacecraft angle), and exhibit on the average slower orbital motions, making the derivation of the orbits intrinsically more difficult. In the case of the Venus L2 option, the advantages are that one can observe around the opposition point, the objects are brighter and move faster, Venus has a faster orbital motion allowing the satellite to scan the sky at a higher rate. The drawbacks are a more difficult data telemetry situation, and a longer and more expensive orbital trip from the Earth to the final destination. Moreover, the thermal environment is generally worse due to the fact of being closer to the Sun (the flux of photons is about twice as intense as that at the distance of the Earth). In order to better quantify the above qualitative considerations, we are currently simulating the efficiency of an Aten/IEO search from these two possible orbital options, using the same code already developed by [6] in a preliminary assessment of the performances of a space-based NEO survey compared with those of ground-based surveys. As an example, some preliminary results of this new analysis are given in Figure 2 for the case of an Aten search carried out from the L2 point of Venus, looking around opposition. In particular, we give histograms of the apparent V magnitudes, phase angle and solar elongation of the objects at the epochs of first detection. Moreover, we give also a plot of the cumulative completeness of the discoveries as a function of time. We used the same orbital and size frequency distributions for the Atens and IEOs as previously adopted in [6]. The simulations assume that the satellite scans every five days an area having a width of 30 degrees in ecliptic longitude, and 90 degrees in ecliptic latitude. Figure 3 is the same as Figure 2, but this time the simulations mimic a survey from the L2 point of the Earth, monitoring a region centered around the point on the ecliptic 60 degrees away from the Sun (and again, 90 degrees wide in ecliptic latitude).

Next Developments: The study is just at its beginning. While the general concept of the mission is already generally sketched, much work is needed to better define the most critical technical details. In particular, an assessment of the cooling concept and its demands in terms of power must be accomplished, as well as a choice of the detectors. Some recent HgCdTe multi-layer sensors, able to measure the thermal flux simultaneously in two or even three separate bands between 5 and 12 μm seem very promising candidates for this mission, in order to apply the NEATM thermal model. One of the most critical open issues, however, seems to be that of the computation of the orbits of the new Atens and IEOs detected by the satellite. Since ground-based follow-up of these objects seems very difficult and unlikely in principle, it should be very important to demonstrate that the satellite alone can be able to obtain observations sufficient for the purposes of orbit determinations. We plan to apply for these purposes the most updated techniques of orbit computation, like the Probability Ranging method developed by K. Muinonen and coworkers. All the above analyses will also be used to decide what is the better orbital option for the satellite (Earth or Venus L2 options). Finally, an assessment of the cost will be decisive to demostrate whether the development of a space-based observing facility for NEO physical characterization can really be a reasonable and cost-effective option, as we tend to believe.

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What we Know and Don't Know about Asteroid Surfaces

Clark R. Chapman (*Southwest Reearch Inst., Boulder*)

One of the most fundamental aspects of mitigating an impact threat by moving an asteroid involves physical interaction with the asteroid. Whether one is bathing the asteroid surface with neutrons, bolting an ion thruster or mass driver onto the surface, or trying to penetrate the surface in order to implant a device below the surface, we need to understand the physical attributes of the surface. Of course, we must understand the surface of the particular body that, most unluckily, is eventually found to be headed for Earth. But, in the meantime, it will advance our ability to design experiments and understand data concerning the particular body if we have thought, in advance, about the range of surface properties we might encounter.

We already know, from meteorite falls, that asteroidal materials can range from strong nickel-iron alloy (of which most smaller crater- forming meteorites, like Canyon Diablo, are made) to mud-like materials (like the remnants of the Tagish Lake fireball event). But the diversity could be even greater, especially on the softer/weaker end of the spectrum, because the Earth's atmosphere filters out such materials. That is why many meteoriticists doubt that we have any macroscopic meteorites from a comet. We could readily expect some icy, snowy, frothy, and dusty materials on the surfaces of asteroids and comets, and perhaps still stranger materials (e.g. with the structure of styrofoam).

A common framework for thinking about asteroid surfaces is to extrapolate from our very extensive knowledge of the lunar regolith. Indeed, there is a considerable literature concerning asteroid regoliths (mostly published in the 1970s and 1980s) based on theoretical extrapolation from lunar regolith models and on inferences from what are termed "regolith breccia" meteorites. These studies suggested that we should expect both similarities and differences from our lunar experience, for asteroids several km in diameter and larger. Less thought was given to smaller asteroids, except that at small sizes there must eventually be a transition to a "bare rock in space."

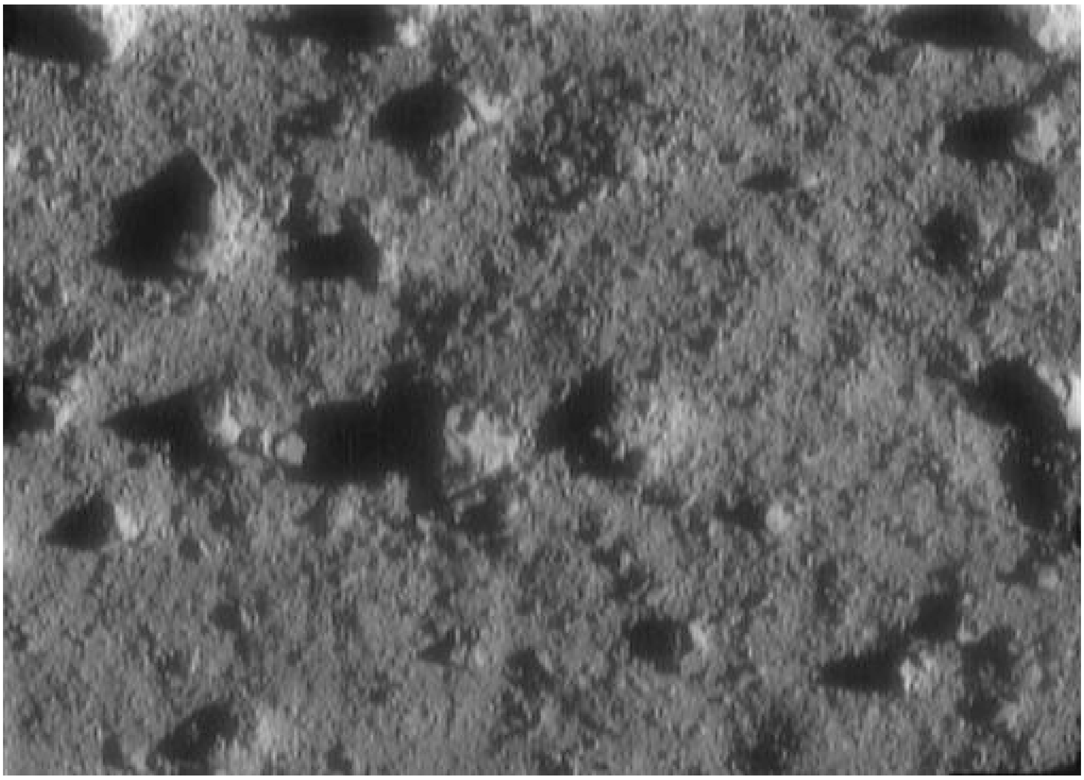
The Earth-approaching asteroid Eros is large enough that it was expected to have a roughly lunar-like regolith, although perhaps somewhat coarser and less well mixed. A major surprise from the NEAR Shoemaker mission to Eros is that its surface is totally unlike the Moon's, particularly at spatial scales of centimeters to tens of meters -- just the scales relevant for human interaction with an asteroid. The Moon is covered with a well-churned regolith (basically a dusty and sandy soil, with occasional larger rocks and boulders, especially near recent craters large enough to have penetrated the several-meter-deep regolith down to bedrock), and its surface is characterized by innumerable small craters. Eros, on the other hand and despite its lunar-like appearance at spatial scales larger than ~100 meters, has been found to have relatively few craters tens of meters in size, and almost no craters cm to meters in size. Instead, the surface of Eros is dominated by countless rocks and boulders, except in localized flat areas (nearly devoid of both craters and rocks) that have been called "ponds". (Examples of high-resolution views of Eros are shown below, with lighting from the right. The top view is the fifth last picture of Eros's surface, showing a surface strewn with rocks and boulders, the largest about three meters across. The final frame shows the transition to a flat terrain, probably a "pond"-like surface within a small crater in which NEAR Shoemaker landed; a basketball has been inserted for scale.)

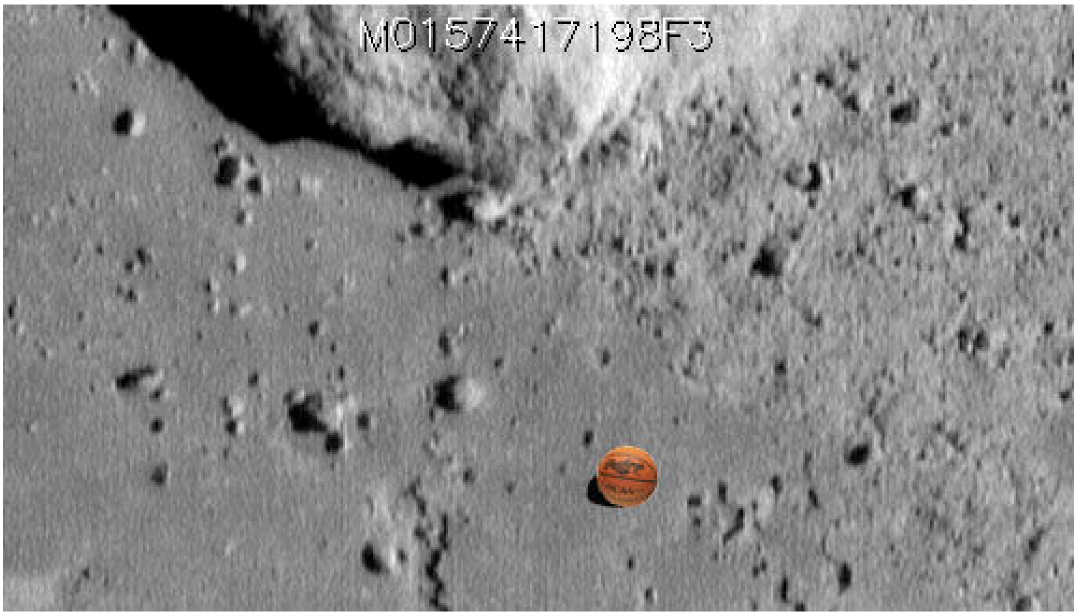
The lesson is that extrapolations from meteoritical and lunar studies proved wrong. Evidently, our generalized understanding of the processes that shape asteroid surfaces is wrong in one or more fundamental ways. The way that we can really tell what an asteroid surface is like is to measure it directly rather than to theorize about it.

It is tempting to draw inferences from the NEAR Shoemaker data about what the surfaces of asteroids, or at least of S-type asteroids, are like. Indeed, it is the best evidence that we have. But, as indicated above, the NEAR Shoemaker surprises are not yet understood, although some hypotheses have been offered. And there is much that we don't know. The ponds are thought by many to be deposits of fine particulates (e.g. electrostatically levitated dust), but our best resolution is only a couple of cm and we do not even know for sure that these surfaces aren't solid and hard. Although the NEAR Shoemaker spacecraft landed on Eros' surface, we never got to see the gouges it may have made.

Even once the NEAR Shoemaker data are thoroughly analyzed, it is not clear how relevant the interpretations will be for asteroid mitigation, which will certainly involve much smaller bodies. In terms of self-gravity, the multi-hundred-meter body we might want to deflect from Earth impact is as different from Eros as Eros is from the Moon. These bodies will likely have essentially no modern regolith on them at all. But there may be legacy regoliths, evolved on the larger bodies from which the small bodies were formed...or almost any kind of unexpected structure.

Although it would seem to be imperative to understand the nature of the surface of any body we want to deflect, our knowledge may always be imperfect. Thus the best deflection technology would be one that is least sensitive to differences in the nature of the target. Those technologies that are inherently low thrust and that distribute force across the broadest cross-section of the body would seem to better meet such an objective.

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IMPLICATIONS OF THE NEAR MISSION FOR INTERNAL STRUCTURE.

A. F. Cheng[1]
[1]The Johns Hopkins University Applied Physics Laboratory, Laaurel, MD 20723, andrew.cheng@jhuapl.edu

On 14 February 2000, the Near Earth Asteroid Rendezvous spacecraft (NEAR Shoemaker) began the first orbital study of an asteroid, the near-Earth object 433 Eros. Almost a year later, on 12 February 2001, NEAR Shoemaker completed its mission by landing on the asteroid and acquiring data from its surface. Previously, on June 27 1997, NEAR performed the first flyby of a C-type asteroid, 253 Mathilde. These two asteroid databases provide a basis for inferences to be made regarding physical properties and internal structure relevant to mitigation.

Results from NEAR Shoemaker's study of Eros include the following (reviewed, e.g., by Cheng 2002). The bulk density is 2.67 +/- 0.03 g cm^{-3}, almost uniform within the asteroid. No evidence was found for compositional heterogeneity or an intrinsic magnetic field. The surface is covered by a regolith estimated at tens of meters thick. A small center of mass offset from the center of figure suggests regionally nonuniform regolith thickness or internal density variation. Blocks have a non-uniform distribution consistent with emplacement of ejecta from the youngest large crater. Some topographic features indicate tectonic deformations. Several regional scale linear features have related orientations, suggesting a globally consolidated internal structure. Structural control of crater shapes hints that such internal structure is pervasive.

Eros is interpreted to be extensively fractured but without gross dislocations and/or rotations (Prockter et al. 2002) - it was not disrupted and reaccumulated gravitationally. Some constraints can be placed on its strength. The consolidated interior must support a shear stress at least on the order of a few bars. Crater morphologies can be interpreted as suggesting a "strength" near the surface of a few tens of kPa.

The NEAR flyby of Mathilde revealed a heavily cratered surface with at least 5 giant craters, close to geometric saturation (see, e.g., review by Cheng 2002). Mathilde's density was unexpectedly low at 1.3 +/- 0.3 g cm^{-3}, indicating a high porosity. Such a porosity may be consistent with a rubble pile structure. This high porosity is key to understanding Mathilde's collisional history, but there are structural features, such as a 20-km long scarp, and polygonal craters indicating that Mathilde is not completely strengthless (Thomas et al., 1999). At least one of Mathilde's structural components appears coherent over a few tens of km.

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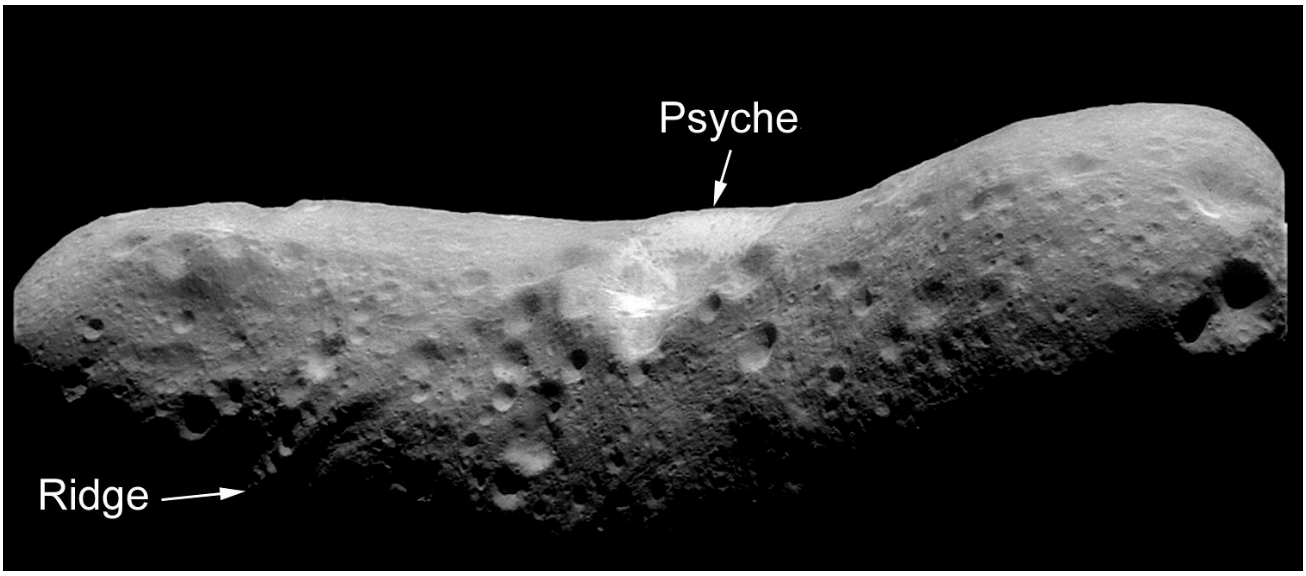

Examples of linear structural features on Eros. These ridge and groove systems areat least several km long and display topographic relief on the order of 100 m (e.g., Cheng et al. 2002). The ridge called out in the figure is approximately coplanar with an 18 km-long ridge system on the opposite side of Eros, suggesting a through-going fracture, and supporting the inference that Eros is not a rubble pile (e.g., Prockter et al., 2002). The 5 km crater Psyche is also called out in the image.

EARTH IMPACTORS: ORBITAL CHARACTERISTICS AND WARNING TIMES. S. R. Chesley, *Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA, (steve.chesley@jpl.nasa.gov)*, T. B. Spahr, *Center for Astrophysics, 60 Garden Street, Cambridge, Massachusetts 02138, USA.*

1 Introduction

The most important requirement, scientific or otherwise, for any impact mitigation is the recognition of the hazard, since, in the absence of a perceived impact risk, there is neither the incentive nor the capability to address the threat. Therefore, the success of any potential mitigation effort will rely heavily upon our ability to discover, track and analyze threatening objects. In this presentation we will consider the effectiveness of the present surveying and monitoring capabilities by bombarding the Earth with a large set of simulated asteroids that is statistically similar to the impacting population.

2 Derivation of Synthetic Impactors

To start, we wish to form a large set of "typical" impactors, and for this purpose we begin with the debiased NEA population model developed by Bottke et al. (2000). Starting with 10^6 values for semimajor axis a, eccentricity e and inclination i that represent the Bottke et al. NEA distribution, we generated $\sim 2\times10^8$ NEAs by adding uniformly distributed longitudes of ascending node Ω and arguments of perihelion ω. This initial NEA set was first reduced to about $58,000$ objects for which the minimum orbital separation, or MOID, is low enough to permit an impact. In this development we call this very low-MOID subset of the NEAs the Potentially Hazardous Asteroids (PHAs), although this is a non-standard usage. According to this definition, the Bottke et al. model predicts about one PHA for every 4000 NEAs.

We next sampled 1000 impactors from among the PHAs according to the fraction of their orbital period that they spend within the capture cross-section of the Earth's orbit, a value that can range from as much as a few percent for Earth-like orbits down to 10^{-9} for low-MOID cometary orbits. This *hazard fraction* f is similar to the impact probability per node crossing, and is distinct from, for example, the Opik (1951) or Wetherill (1967) impact probabilities, which average the impact probability over the precession cycle of the object. Deriving the impactors in this way allows for the more hazardous orbital classes, such as low inclination, Earth-like or tangential orbits, to have appropriately increased prominence among the simulated impactors.

3 Impactor Orbital Characteristics

It can be instructive to compare the orbital characteristics of the entire NEA population with the PHAs and the debiased impactors. Figure 1 compares the distributions of a, e, i, q and Q, where q and Q are the perihelion and aphelion distances, respectively. From this figure and from Table 1, it is clear that the impacting population has several distinct features. For instance, Earth-similar orbits are prominent among the impactors, as evidenced by the relative excess of impactors with $a \simeq 1$ AU, low e and low i. Indeed, low-inclination orbits are strongly predominant among the PHAs, and even more so among the impactors. We also note that shallow crossing orbits, i.e., those with either q or Q within 0.05AU of the Earth, have a substantially increased prominence among the impactors. The interior shallow crossers, in particular, have a ten-fold increase in the impacting population, when compared to the PHA population.

In general, the encounter and impact velocities of the PHAs are significantly greater than those of the impactors. Figure 2 compares the cumulative distributions of impact and encounter velocities between the PHA and impactor sets. The impact ve-

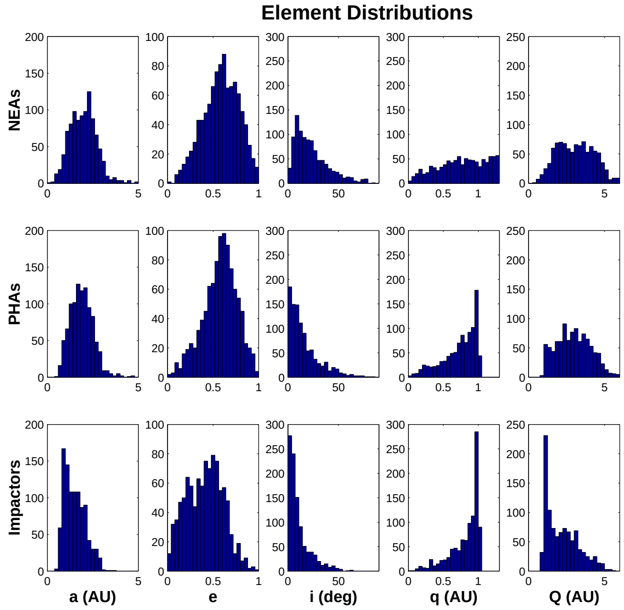

Figure 1: Orbital characteristics of NEAs, PHAs and impactors.

Table 1: Orbital characteristics of NEA subpopulations.

	NEAs (%)	PHAs (%)	Impactors (%)
Shallow Crossers			
Interior ($Q < 1.05$ AU)	1	1	11
Exterior ($q > 0.95$ AU)	8	22	38
Deep Crossers	61	77	53
Atens ($a < 1$ AU)	7	7	23
Low inclination ($< 5°$)	6	25	38
Low V_∞ (< 10 km/s)	–	15	53

locity, which is a good indicator of the ΔV cost for spacecraft rendezvous (and hence impact mitigation), has a median about 5 km/s less for impactors than for PHAs. This is due to the predominance of low-i shallow-crossing orbits for impactors.

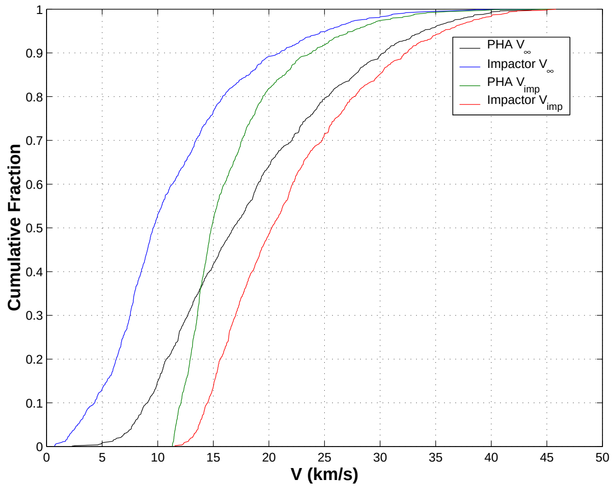

Figure 2: Cumulative distributions of impact and encounter velocities for the PHA and impactor sets.

Carusi et al. (2002) describe a simplified formula for computing the velocity change required to deflect an asteroid by a given distance within a specified time interval. Using their approach, we can compute the required ΔV to deflect each impactor as a function of lead time. Taking the geometric mean of these values we find the relation

$$\Delta V = \frac{0.035 \text{ m/s}}{T},$$

where T is the number of years before impact that the impulse is applied. This is half the value offered by Ahrens and Harris (1994), a very good agreement considering that the dispersions around this geometric mean are more than an order of magnitude.

To this point, we have attached no sizes to our set of impactors, and in fact we really don't need to do so, although we will assume that all have the same absolute magnitude. For this approach to be meaningful we have to accept the hypothesis that there is not a correlation between size and orbit among the NEAs, so that the synthetic impactor set represents the true impactor population, no matter the size. Thus, with this approach, we assume that our impactors are statistically similar to the next 1000 impactors at a given size or in a given size range.

4 Impactor Observability

With our impactors in hand, we wish to see how and where they are observable in the decades leading up to collision. To answer this question, we selected the LINEAR Experimental Test Site, near Socorro, New Mexico, as the observing location. We consider an object observable if it is situated at least 60° from the Sun, with proper motion in the range 0.05–$10.0^\circ/\text{day}$ and at no more than 3 air masses. Furthermore, it must be brighter than the detection limit of the supposed survey telescope.

The question of whether an object is bright enough depends directly upon its assumed size and upon the survey's assumed limiting magnitude, or depth. In preparing the ephemerides, we only calculated the difference between the visual magnitude and the absolute magnitude, $S = V - H$. Given an assumed absolute magnitude H and survey limiting magnitude V_{lim}, the object is considered bright enough to be detected if $S + H < V_{lim}$, or equivalently if $S < V_{lim} - H$. For this report, we will vary the assumed H, while assuming a survey depth of $V_{lim} = 20$ throughout. This allows us to frame our results in terms of absolute magnitude, rather than the much less intuitive $V_{lim} - H$. However, this also means that any of these results can be applied to a different survey depth simply by incrementing or decrementing the quoted H-value.

Figure 3 indicates the sky-plane density of the 1000 impactors over the 100-year period leading up to impact. The plot indicates clearly that, for a $V_{lim} = 20$ survey, the most favorable region to search for $H = 18$ impactors is near the ecliptic between solar elongations of 60° and 90°. There is also a modest concentration at opposition that stems from the fact that objects are brightest at full phase. On the other hand, the low elongation peaks are present because the sky density of objects is much higher as we look through the "belt" of impactors. However, as the elongation increases, the increasing density of objects is eventually overcome by the decreasing brightness due to phase losses. These phase losses are more severe for smaller objects, and the corresponding plot for $H = 20$ shows the low-elongation peaks are less significant than the opposition peak. For $H = 22$, the low-elongation peaks are no longer significant. We note that this sky distribution differs significantly from similar plots for the NEA population because the impactors tend toward lower inclinations and lower relative velocities.

Another approach to plotting the sky density of impactors is to weight them according to their likelihood of collision. In other words, instead of weighting all objects equally when accumulating the results, we can weight them according to the hazard fraction f described in Sec. 2. The result of this alternate approach, which can be thought of as mapping impact probability onto the sky, is presented in Figure 4 for the same data set used in Fig. 3. The results indicate clearly that the *hazard*-density approach even further accentuates the low-elongation regions over the opposition region, as compared to the *impactor*-density plots. Indeed the hazard density is predominantly at low elongation for sizes as small as $H = 22$.

For various reasons, searching the near-sun region is more operationally challenging than searching near opposition, where present survey efforts have been concentrated. Also, current survey strategies are tailored towards fulfilling the Spaceguard goal of finding all NEAs larger than 1 km in diameter, and searches for NEAs, as opposed to impactors, are clearly the most productive around opposition since so many NEAs are of the Amor class, with orbits completely exterior to the Earth's.

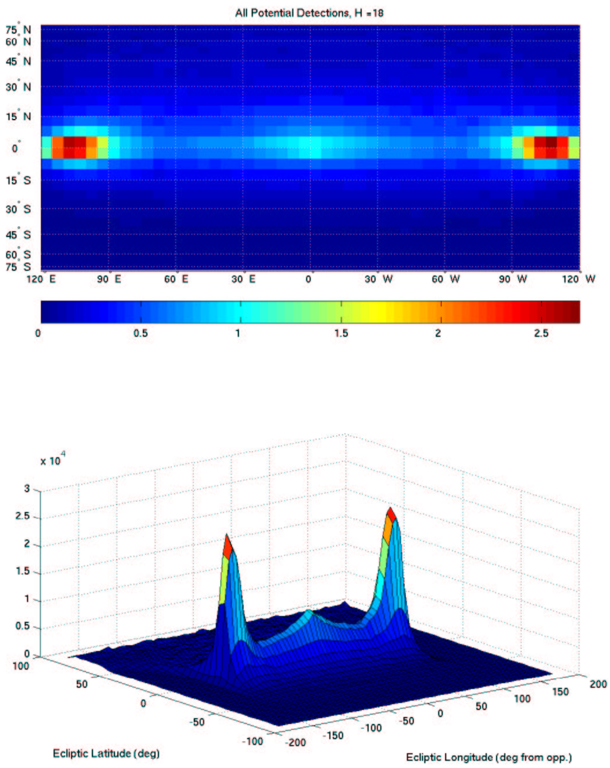

Figure 3: Sky-plane distribution of $H = 18$ impactors at LINEAR's ETS, assuming a survey depth of $V_{lim} = 20$.

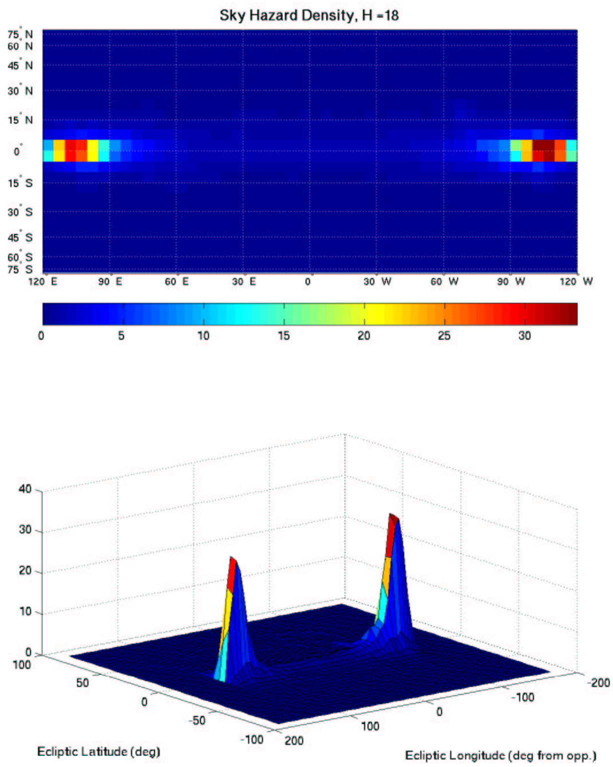

Figure 4: Sky-plane distribution of impactor hazard. Same as Fig. 3, except the residence times in each bin are weighted according to the associated hazard fraction f for that object.

On the other hand, a search for large impactors is not expected to find such an object over human timescales, simply because large impacts are so rare. However, if a large NEA *is* set to impact the Earth in the next century it will most readily be detected far from opposition, as we show in the next section.

5 Survey Simulations

Given ours set of impactors, one can ask whether and when they would be discovered by various NEO surveys with differing sky coverages and faint limits. To this end, we simulated two fictitious NEO surveys over the century prior to impact. The first survey, dubbed "OPPOSITION," is based loosely on the strategy and capability of the LINEAR system (Stokes et al., 2000), the world's most prolific discoverer of NEOs. OPPOSITION covers the ecliptic and opposition regions heavily with modest coverage at higher ecliptic latitudes, but no coverage at solar elongations less than 90°. The survey model assumes 75% clear weather and some down time due to lunar interference. Figure 5 indicates the distribution of the mean time between detection by OPPOSITION for the synthetic impactors at various sizes. We note from this chart that the mean time between detection for most impactors larger than $H = 20$ will be a few decades or less.

Another interesting result that can be extracted from the data is the detection lead time. Figure 6 depicts the fraction of impactors that were serendipitously detected by OPPOSITION before impact as a function of the time until impact and as a function of absolute magnitiude. For example, the plot indicates that 48% of $H = 24$ impactors will be detected sometime in the century leading up to impact, and that only 20% will be detected in the last year before impact. Similarly we can see that, for $H = 20$ objects, about a third will be serendipitously detected in the last month before impact, whereas 12% will be detected in the last week befor impact. Differencing these two numbers tells us that roughly 20% of previously undiscovered $H = 20$ impactors will be detected with 1–4 weeks of warning time, which, in principle, could be sufficient to mount an effective evacuation of the impact region or threatened coastal regions.

Figure 6 also indicates that OPPOSITION would only detect 98% of objects, no matter the size. This is because the survey never looks beyond 90° from opposition, and so some shallow-crossing interior objects rarely enter the search region. To further consider this point we tested a second survey strategy, with equipment and location similar to OPPOSITION. However, this survey, which we call "NEAR-SUN," never searches near the opposition region, instead concentrating exclusively on the high denstity regions indicated in Figs. 3 & 4. Specifically, NEAR-SUN trolled for impactors within 15° of the ecliptic and at solar elongations ranging from 60° to 110°. Figure 7 compares the two surveys' impactor completeness as

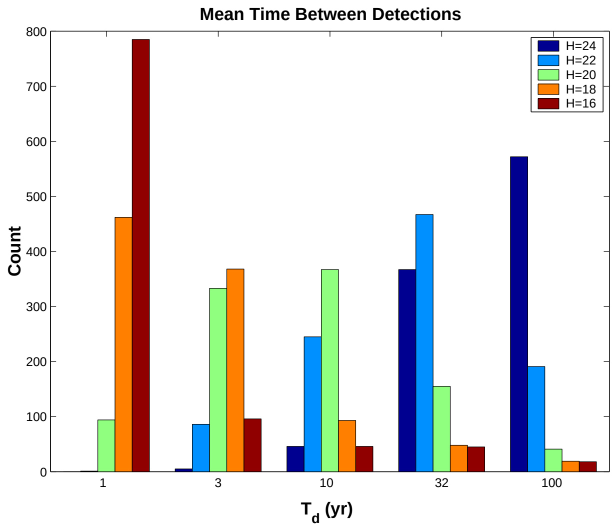

Figure 5: Histogram of mean time T_d between detections for impactors at various absolute magnitudes, for the OPPOSITION survey. Objects that escaped detection over the entire simulation are included in the 100-year bin.

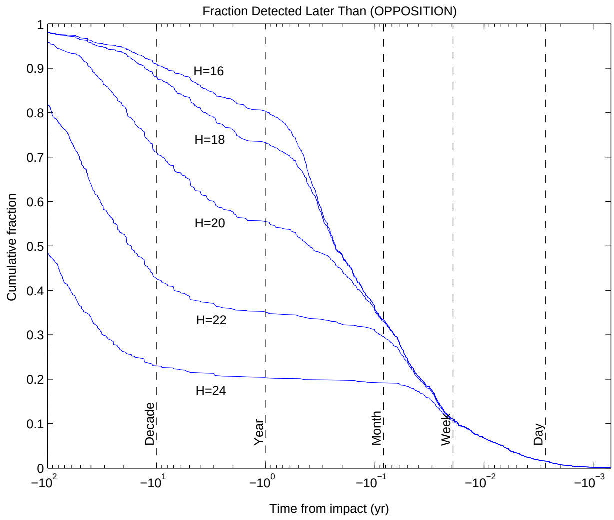

Figure 6: The fraction of impactors serendipitously detected later than a given time before impact, for the OPPOSITION survey.

a function of time prior to impact for several different impactor sizes. From that plot it is clear that NEAR-SUN beats OPPOSITION at detecting large impactors ($H \leq 18$), especially when the completeness exceeds 80%. But for smaller objects the phase losses prevent NEAR-SUN from discovering objects as rapidly.

We can measure survey completeness by the number of objects detected, as in Fig. 7, or we can measure completeness by the percentage of the aggregate risk detected, in much the same way as Fig. 4 projected the risk onto the sky. The result of this approach is given in Fig. 8, where we can see that, despite its very limited sky coverage, NEAR-SUN is markedly better at detecting the most hazardous large impactors, even excelling as faint as $H = 20$. Note also that the 2% of impactors that went undetected by OPPOSITION during the 100-year simulation actually comprised about 6% of the hazard. This is because the interior shallow-crossing objects that were missed hold a disproportionate share of the aggregate impact risk.

The obvious conclusion from these results is that the near-sun region should not be neglected when searching for large impactors. However, given that this region of sky is only observable for a few hours each morning and evening, the remaining telscope time could be used for an opposition-type survey, thus concentrating on the two most productive areas of sky to survey for the most hazardous objects. We also remind the reader that the size results given in this section are for a survey depth of $V_{lim} = 20$. For a fainter survey, the absolute magnitudes need to be adjusted accordingly. For example, if we extend the survey to $V_{lim} = 24$, the proposed limit of the recently announced PanSTARRS project, then Fig. 8 indicates that the NEAR-SUN strategy would be more effective than OPPOSITION's for all sizes of interest ($H \leq 24$).

6 Warning Time: Post-Detection Issues

The detection lead time is important in determining the time available for mitigation, but it is not the only factor. There are several hurdles to be crossed before an object is announced to the community. The first among these is the recognition that an object has unusual motion. If a survey makes this determinaion it calls out the detection when forwarding the data to the Minor Planet Center (MPC). If the MPC staff agrees with the assessment then it is placed on the WWW NEO Confirmation Page for verification by other observers. If the object is followed and confirmed to be an NEA then the MPC will issue a discovery announcement. At any of these steps a potential impactor detection could be scrapped and thus escape discovery. It is well known that this actually happens, but it is very difficult to assess the extent to which these factors delay discovery of NEAs.

There is also some delay between the discovery of the asteroid and the recognition that it poses a threat worthy of mitigation. The idea of continually monitoring the ever-evolving asteroid orbit catalog for possibilities of impact is fairly new, and the first automatic collision monitoring system was fielded less than three years ago. Today there are two independent and parallel systems, at JPL[1] and the Univ. of Pisa[2], that are operating continuously to scan for potential impacts. These efforts have been very successful at detecting potentially hazardous future encounters for newly discovered asteroids and reporting the results to the NEO community. Follow-up observers have responded enthusiastically with observations that permit the hazard assessment to be refined and usually eliminated.

[1] http://neo.jpl.nassa.gov/risk
[2] http://newton.dm.unipi.it/neodys

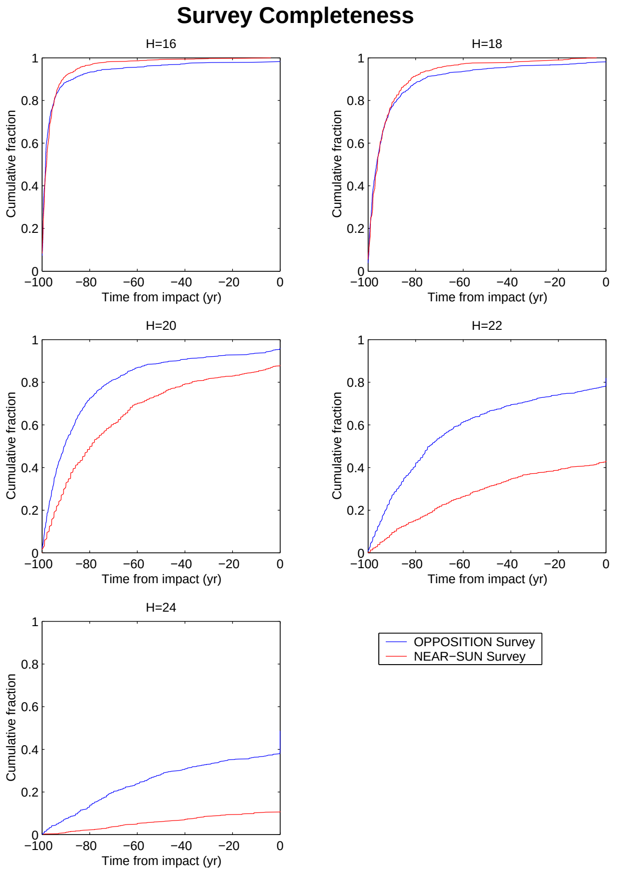

Figure 7: Comparison of OPPOSITION and NEAR-SUN survey performance, in terms of impactor completeness.

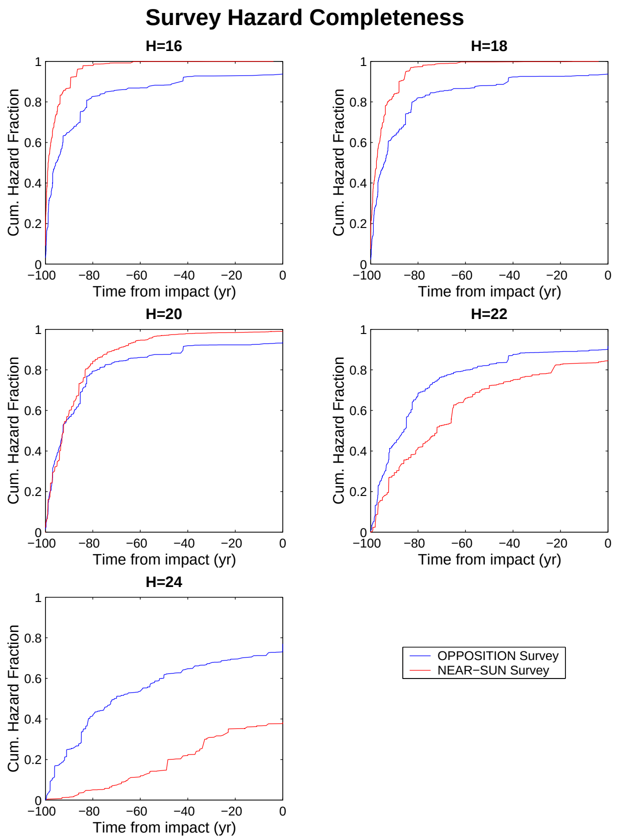

Figure 8: Comparison of OPPOSITION and NEAR-SUN survey performance, in terms of impact hazard completeness.

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OPTIMAL INTERCEPTION AND DEFLECTION OF EARTH-APPROACHING ASTEROIDS USING LOW-THRUST ELECTRIC PROPULSION. B. A. Conway, Dept. of Aeronautical & Astronautical Engineering, University of Illinois, Urbana, IL 61801. bconway@uiuc.edu

Introduction: The spectacular collision of the Shoemaker-Levy 9 asteroid with Jupiter in July 1994 was a dramatic reminder of the fact that the Earth has experienced many similar events and will continue to. A consensus is developing that while the probability for collision is low the potential for destruction is immense and thus some resources should be devoted to threat detection and possible interdiction. In this work optimal (minimum-time) trajectories are determined for the interception of asteroids which pose a threat of collision with the Earth. An impulsive-thrust escape from the Earth is used initially to reduce flight time but is followed with continuous low-thrust propulsion using values of thrust and specific impulse representative of electric motors. The continuous optimization problem is formulated as a nonlinear programming problem using the collocation method in which the differential equations of motion are included as nonlinear constraint equations. The use of low-thrust propulsion after Earth escape is shown to dramatically decrease the mass of the interceptor vehicle at launch, or alternatively, dramatically increase the payload mass for a given total interceptor mass.

One method suggested for the prevention of the collision of an asteroid with the Earth is to deflect it from its course, perhaps using the explosion of a nuclear weapon. Solving the optimal control problem to maximize explicitly the miss distance of the asteroid is problematic, but a two-stage approach in which the time to interception, for a given interceptor launch date, is first minimized and then the direction of the deflecting impulse is optimized to maximize the subsequent deflection should in principle yield nearly the same result. Optimizing the deflection for a given date of interception is shown to require only the asteroid orbit state transition matrix, that is, it is independent of the trajectory of the intercepting vehicle.

Method: The spacecraft is assumed to depart the Earth using an impulse, perhaps provided by the upper stage of its launch vehicle. The position in low-Earth orbit and direction of the impulse are chosen by the optimizer. Once independent of Earth, the spacecraft uses low-thrust, electric propulsion to take it to asteroid interception in minimum time. With thrust on, the orbit elements are continually varying The variational equations used are those for the equinoctial elements.

The problem is then to choose the time history of the thrust pointing angles □ (in-plane) and □ (out-of-plane) in order to minimize the performance index, which is the time of flight, subject to satisfaction of the system variational equations, the system initial condition constraints, and the terminal constraint (of interception):

The problem is solved using the method of direct collocation with nonlinear programming (DCNLP) [1-3]. In this solution method the continuous problem is discretized by dividing the total time into "segments" whose boundaries are termed the system "nodes". Each state is known only at discrete points; at the nodes and, depending on how the problem is formulated, at zero, one, or more points interior to a segment.

The discretized problem becomes a nonlinear programming (NLP) problem. The parameters are the state variables (which are the 6 spacecraft orbit equinoctial variables + the thrust acceleration) at the nodes and center points of the segments and the control variables (the two thrust pointing angles) at the nodes, center point, and collocation points of each segment. There are a few additional NLP variables such as the final time and the 2 initial pointing angles for the hyperbolic excess velocity of Earth escape. The system nonlinear constraints are the "defect" equations which enforce satisfaction of the differential equations, the initial condition constraints and the conditions for interception.

Example: Optimal trajectories have been found for the interception of Earth-approaching asteroid 1991RB [4]. Its orbit elements are, as of 9/15/1991,

$a = 1.4524$ AU, $e = .4846$, $i = 19.580°$

□ $= 359.599°$, □ $= 68.708°$, $M = 328.080°$

which are very typical of Earth approaching asteroids. This asteroid approached the Earth to within .04 AU, or 15 lunar distances, on 9/19/1998. It is assumed for the following example that launch from Earth takes place 6 months prior to the close approach, that is, on 3/19/1998. A constant thrust acceleration of $8.46 \cdot 10^{-5}$ g is assumed and the specific impulse of the electric motor is 4000 sec. The resulting optimal trajectory is shown in Figure 1. The time of flight is 2.5096 TU = 145.9 days. The time histories of the optimal thrust pointing angles are shown in Figs. 2 & 3.

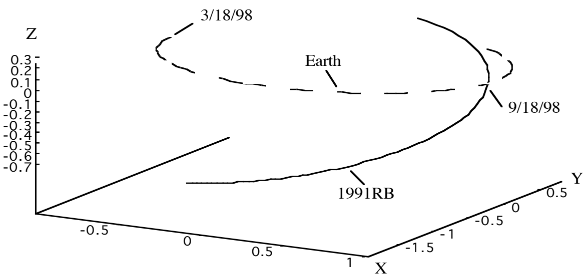

Figure 1 Optimal Trajectory for the Interception of Asteroid 1991 RB

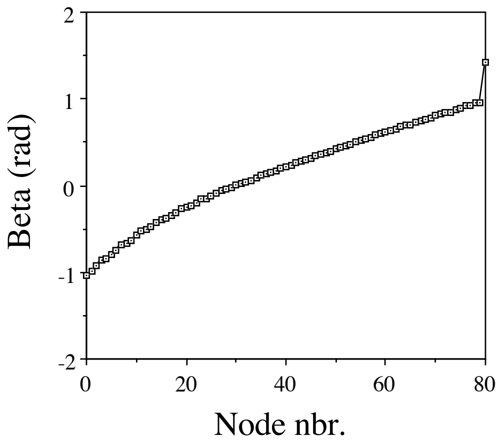

Figure 2. History of the In-Plane Thrust Pointing Angle for the Interceptor

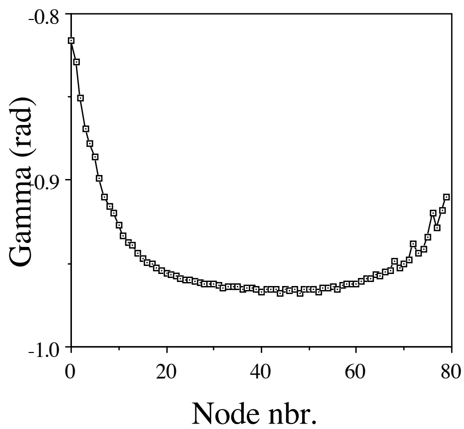

Figure 3 History of the Out-of-Plane Thrust Pointing Angle for the Interceptor

Using values for structural coefficient and specific impulse representative of current technology, we have shown that a two-stage conventional chemical rocket duplicating the mission shown in Fig. 1, i.e. intercepting the asteroid in the same 146 day flight time, would have a payload of approximately 1 to 2% of mass at ignition. However, the much more efficient low-thrust vehicle would have a payload mass of approximately 12% of mass at ignition, a very substantial improvement.

Maximization of the Deflection: Work has also been done on the problem of optimizing the deflection of the dangerous asteroid, at the time of its close approach to Earth, by a given impulse applied at an earlier time. [5] We assume that a collision (or near-collision) is imminent, i.e. will occur before the asteroid has made another complete revolution about the sun. We show that a near-optimal determination of the direction in which an impulse should be applied to the asteroid, as well as the resulting deflection, can be found without any explicit optimization. The method is easily applied to the true, three-dimensional geometry of the problem.

At the time of interception t_0 the system state transition matrix $\Phi\left[t, t_0\right]$ determines the perturbation in position ($\delta \mathbf{r}$) and velocity ($\delta \mathbf{v}$) which will result at time t due to a perturbation in position and velocity applied at t_0 , [6] i.e.,

$$\begin{bmatrix} d\bar{r} \\ d\bar{v} \end{bmatrix} = F(t, t_0) \begin{bmatrix} d\bar{r}_0 \\ d\bar{v}_0 \end{bmatrix} = \begin{bmatrix} \tilde{R} & R \\ \tilde{V} & V \end{bmatrix} \begin{bmatrix} d\bar{r}_0 \\ d\bar{v}_0 \end{bmatrix}$$

Therefore

$$\delta \mathbf{r}(t) = \left[R\right] \delta \mathbf{v}_0 (t_0)$$

where the Φ matrix is the system state transition matrix and R is a 3x3 submatrix of this square matrix.

We want to maximize

$\left|\delta \mathbf{r}(t_c)\right| = \max\left(\left[R\right]\delta \mathbf{v}_0\right)$ where the time of interest, t_c, is the time of close approach to Earth. Equivalently we may maximize $\partial \mathbf{v}_0^{\,T} \left\|R\right\|^T \left\|R\right\| \partial \mathbf{v}_0$. This quadratic form is maximized, for given δv_0, if $\delta \mathbf{v}_0$ is chosen parallel to the eigenvector of $\left[R\right]^T\left[R\right]$ that is conjugate to the largest eigenvalue of $\left[R\right]^T\left[R\right]$. This yields the optimal direction for the perturbing velocity impulse, $\delta \mathbf{v}_0$ which will be expressed on the space-fixed basis since this is the basis on which [R] is implicitly expressed.

Figure 4 shows the maximum amount of deflection which can be obtained, at what would otherwise be the time of close approach to the Earth, as a function of the interval between interception and close approach of the asteroid 1991RB (on 19 September 1998). The impulse is assumed to be applied to the asteroid in the direction chosen, as described in the previous section, to maximize the deflection at the subsequent close approach. The figure shows that, if the asteroid is reached several months before the time of collision, each 1 m/sec of velocity change imparted to the asteroid may yield a deflection distance comparable to the width of the Earth.

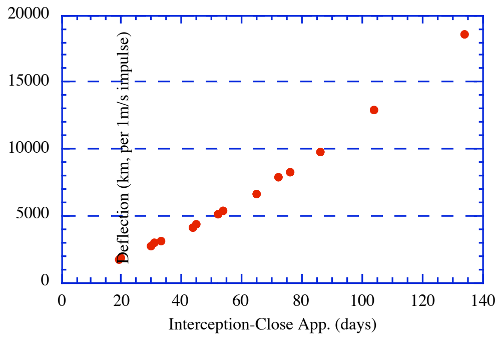

Figure 4. Optimal Deflection (km. per 1 m/sec of deflection velocity) vs. Time to Close Approach

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Physical properties of comets and asteroids inferred from fireball observations

M. Di Martino, INAF - Osservatorio Astronomico di Torino, 10025 Pino Torinese, Italy, dimartino@to.astro.it

Introduction: Fireballs (or bolides) are very important events to derive basic physical information on near-Earth objects in a size range for which detection using conventional astronomical techniques is particularly difficult. The observable features of these events can provide relevant information about the physical properties of their parent bodies, and their likely origin. This may be important, for instance, to better evaluate the relative abundance of bodies having a likely cometary origin.

At the same time, a better estimate of the frequency of fireball events can put essential constraints on the general trend of the near-Earth object (NEO) size distribution, by providing data referring to an interval of the mass spectrum that is very poorly known at present. The major problem in fireball observations, however, is that currently only a minor fraction of the events are actually detected and recorded, and detections occur mostly in the form of serendipitous discoveries made mainly by classified satellites devoted to other purposes, thus natural events, like bolides and airbursts, may be either overlooked or ignored. The situation can drastically improve if dedicated observing facilities will be developed. Due to the large areas of sky to be monitored for efficient fireball detection, the development of a dedicated space-based system is strongly needed.

The influx of cosmic material on the Earth: The interplanetary material falling on the Earth each year (averaging the influx over 100 years) is estimated to be about 24,000 tons, and it is known that interplanetary objects of decameter size of probable cometary origin form the most important part of this influx (about 80%). Nevertheless, they are also the least known population of interplanetary bodies. This is due to the inherent difficulty to carry out systematic and global observations using the present ground-based instrumentation and classified satellite data.

Bodies with mass larger than about 0.1 kg produce fireballs, and our knowledge on them comes mainly from photographic observations. Meteors brighter than magnitude –17 are called superbolides, while those of about magnitude –4 and brighter are called bolides or fireballs.

The association of a meteor to its parent body comes first of all from a dynamical aspect. The calculation of its orbit from the observed dynamical parameters may allow associating these bodies to comets or asteroids, but a definitive confirmation of the actual nature of the original meteoroid can come only from the analysis of the recovered meteorites. In other words, meteoroid orbits cannot be solely used to classify bodies of decameter size as cometary or asteroidal.

Meteor observation: The atmospheric interaction of meteoroids is a primary tool to characterize their population, including dynamical, physical and chemical properties. The parameters we can obtain from meteor observation are: velocity, trajectory, beginning and terminal (end) heights of the luminous phenomenon, luminosity (lightcurve), and spectrum. From these data, the most important problems in the physics of meteors we have to solve are the determination of their mass, density, structure and chemical composition, but this is a challenging task.

To obtain these values, we need good and precise observations of the meteor phenomenon; moreover, we need homogeneous material for statistical purposes. The comparison between observed and theoretical (modeled) values allows us to obtain information on the principal physical characteristics of meteoroids (size, bulk-density, structure, strength and porosity).

Observation of fireballs can provide us data to test theories for fragmentation, which can be also valid for larger bodies. The monitoring by space-based sensors of the whole globe, with the aim at following the atmospheric trajectories of decametric size meteoroids, certainly is the best way of getting direct data on these bodies. We have to collect data on largest bodies observable in the atmosphere, which finally may overlap with those available on smallest asteroids observed by ground-based NEO discovery programs.

Bolide detection from space-based sensors: Satellite sensors currently detect bolides with peak brightness greater than about –17 visual magnitude, recording some 30-50 such events each year. Events of this size are believed to represent impact of masses 1,000 kg and larger. In general, they are not associated with meteor showers, so are called sporadic. Events developing energies of about or larger than 10^{-4}kt (about 10^{8} J ÷ 1kt = 4.185×10^{12} J) are estimated about 10,000-30,000 per year (for comparison, typical shower meteors have kinetic energies of about 1-10 J). Initial kinetic energies of the events detected by satellite-based sensors are equivalent to energy of 0.05-40 kt. For typical velocities of 15-20 km/s, this corresponds to masses in the range of 1-1,000 tons.

The advantages of satellite observations are obvious. Meteoroids deposit most of their kinetic energy at altitudes below 60 km (mainly between 30 and 45 km), the observations can be made 24 hours a day, above cloud decks, and through a thin atmosphere shell. *Ad hoc* imaging visual and IR systems could certainly improve the present detectability rate. Moreover, more precise trajectories (relying on multiple satellite observations) and information on atmospheric impacts of the smallest NEOs could be collected. Such a space system could help to fill in the gap between telescopic observations of NEOs and the smallest cosmic planetary bodies, thus allowing to obtain the missing data between 10^3 and 10^6 kg mass interval and defining the size distribution of NEOs at these sizes. In addition, the knowledge of the minimum dimensions of the bodies that can reach the ground is extremely important to assess the minimum risk threshold. Giving a more accurate account of this population of small bodies may provide the opportunity to predict the probability of their impact.

Eventually, the virtually unrestricted viewing from space would permit accurate spectral measurements over a wide range of wavelengths, from the ultraviolet to the infrared. These would be a useful tool in determining the chemical compositions and the temperatures of the fireballs, deriving information about the parent body, and thereby in obtaining clues as to the type of object the parent body was.

Conclusion: Data obtained by visible and infrared sensors placed on-board spacecrafts, as those that will form in the next future the *Galileo* European GPS satellite constellation, which will cover continuously the entire globe from an height of about 23,600 km, would be one of the best possibility to monitor meteor phenomena developing relatively high energies. Moreover, a global and systematic monitoring of the Earth globe from space could allow obtaining statistically significant information on the size-frequency distribution of impacts and probability on the occurrence of Tunguska-class airbursts.

We have to consider also that such a space system would be a powerful tool in helping to avoid misidentification of bolide detonations as a nuclear attack - with the connected global security implications - especially in the case of potential combatant nations having nuclear weapons but that do not dispose of sophisticated surveillance systems. Mitigation, in fact, means also to protect us from possible “secondary” consequences due to the interaction of relatively large cosmic bodies with the atmosphere.

MASS DRIVERS, A ROBUST SOLUTION FOR PLANETARY DEFENSE. Freeman Dyson,[1] George Friedman,[2] and Lee Valentine[3], [1]Space Studies Institute (P.O. Box 82, Princeton, NJ 08540, dyson@ias.edu), [2]Space Studies Institute (P.O. ox 82, Princeton, NJ 08540, HPrimate@aol.com), [3]Space Studies Institute (P.O. Box 82, Princeton, NJ 08540, lsvalentine@att.net).

Introduction: The mass driver reaction engine is one kind of electromagnetic rocket. Sequentially energized circular drive coils form the barrel of the engine. These coils accelerate a solid or liquid propellant carried in the bucket coil down the barrel of the engine. The bucket coil surfs on a traveling magnetic wave produced by the drive coils. Dynamic magnetic levitation prevents the bucket's touching the walls of the engine's barrel. Laser sensors measure the velocity of the bucket and dynamically adjust the drive coils' firing. The engine is thus compensates automatically for faulty coils, capacitors, or other components.

Early designs were aimed at transporting tens or hundreds of thousands of tons of aluminum, silicon, and glass from the lunar surface to geostationary orbit in support of solar power satellite construction.[1] It soon became obvious that the new high-performance mass drivers were well-suited to moving asteroids for mining purposes and for planetary defense.[2]

Mass drivers have some singular advantages for a long duration mission in an unforgiving environment. They are rugged. Their use does not require protection against high temperatures. They can convert electrical energy to thrust with an efficiency of more than 95%. The design of mass drivers has benefited enormously from recent advances in solid-state power switching devices and in ultracapacitors. A space engine could use off the shelf components. Because of its inherent rugged construction, mass drivers should be able to be relied on for the years long thrusting necessary to divert global killer asteroids.

Mass drivers are unique among engines already developed for deep space transportation in that, unlike other concepts, they do not require bringing along large masses of special propellants.

The major advantage of this approach is that all the energy can come from the sun and all the reaction mass is obtained from the mass of the asteroid itself. The only mass that needs to be transported to the asteroid is that of the processing equiptment, power supply and acceleration coils which convert electrical energy to kinetic energy.

For the rare objects that could cause global damage, warning-times are likely to be long and the mass-driver can be used effectively to avoid impacts. To give an idea of the power required to operate the mass-driver, consider a NEO with mass one billion tons, a mass driver with a throw-velocity of 100 meters per second and a system efficiency of 50 percent, and a warning-time of ten years. Then the power required to move the object by 5 earth-diameters and safely avoid the impact will be 140 kilowatts. This is a modest amount of power that could easily be supplied by solar collectors or by a small nuclear reactor. Such a mass driver engine would fit comfortably in the back seat of a car.

SSI researchers at Princeton University have developed critical mass driver subsystems to technology readiness level 6 under contract to NASA and with private funding.[3] Specific impulse greater than hydrogen oxygen chemical rockets is achievable but appears unnecessary for the purpose of moving asteroids or comets.[4]

Such a machine could be a bit better or a bit worse depending on the talent of the engineer, but we expect no fundamental show stoppers to the construction of an engine adequate to deflect even large asteroids, given a reasonable lead time. No design surprises are expected, a mass driver of adequate performance should be able to be constructed with straightforward engineering. The use of a superconducting bucket coil appears to offer improved performance relative to ohmic bucket coils.[5]

Mass drivers do not require a nuclear power source, a solar power source similar to that used on the international space station will be sufficient to power the mass driver during its operational lifetime.

Historical note on mass drivers:

1953 Arthur C. Clarke, now Sir Arthur, describes an electromagnetic catapult for launching material from the moon in the Journal of the British Interplanetary Society.

1974 Gerard K. O'Neill describes a lunar catapult called a mass driver. The first mass driver is built at MIT in 1975.

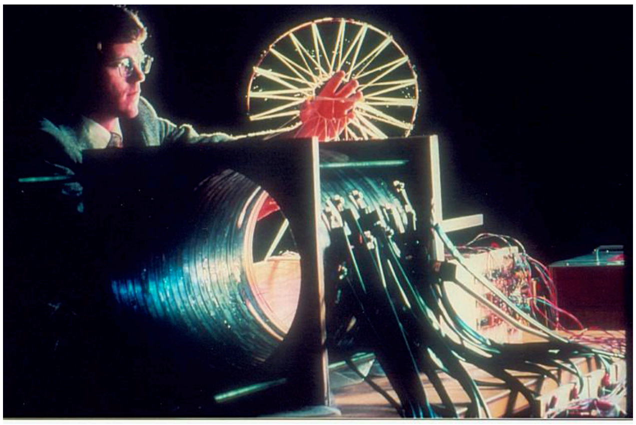
1979 to 1981 the Space Studies Institute builds mass driver model II at Princeton with funding from NASA and private sources.

1981 to 1983 A new magnetic field geometry machine called the long wave pull only mass driver increases performance and simplifies design using ohmic buckets.

1983 SSI completes Mass Driver III at Princeton.

2001 Space Studies Institute and Carnegie Mellon University's Robotics Institute begin collaboration on mass driver setup and operation.

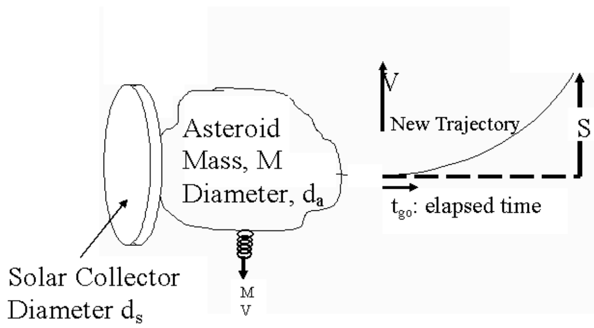
Mass Driver Model III



Dr. Les Snively holding a mass driver bucket coil in the background. The drive coils form the barrel of the mass driver engine in the foreground. Power cables trail off to the right.

Remarkable progress was made in reducing the size and weight of the mass driver over the course of a nine-year development program. Dr. Brian O'Leary at the Space Studies Institute pointed out the utility of mass drivers for returning small asteroids to high Earth orbit for use in a program of solar power satellite construction in 1979.{2] Following the publication of that article, mass drivers decreased in size and complexity and the threat of near Earth objects began to be appreciated, making his conclusions all the more relevant.

Mass Drivers Applied to Planetary Defense.



Noteworthy $v_f = at$; $s = \_\ at^2$

Therefore $v_f = 2\,{}^{s}/_{t} = 2v_{ave}$

For a body under constant acceleration, the final velocity = 2 times the average velocity

Energy and Momentum:

Energy: $E = \frac{1}{2}MV^2 + \frac{1}{2}mv^2$

Momentum: $MV = mv$

Let $K = \frac{v}{V} = \frac{M}{m}$

Substituting: $E = \frac{1}{2}KmV^2 + \frac{1}{2}mK^2V^2$

Ratio of Asteroid KE to Ejecta KE:

$$\frac{AsteroidKE}{EjectaKE} = \frac{\frac{1}{2}KmV^2}{\frac{1}{2mK^2V^2}} = \frac{1}{K}$$

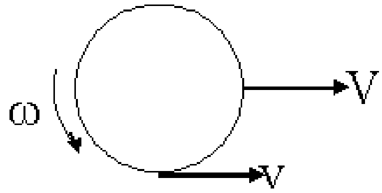
Only $\frac{1}{K+1}$ of the available energy couples to the asteroid

For example, for v = 300 m/sec, V = 2.6 m/sec

Less Than 1% of E couples with the asteroid.

"Paradoxically" It ges worse, as mass driver ejecta velocity increases time-to-go increases for a given power supply.

Rotational vs Translational KE:



Translational: $KE = \frac{1}{2}mV^2$

Rotational: $KE = \frac{1}{2}I\omega^2$

$I = \frac{2}{5}mr^2$

$\omega = \frac{v}{r}$

Therefore: $\frac{TranslationalKE}{RotationalKE} = \frac{5}{2}\left(\frac{V}{v}\right)^2$

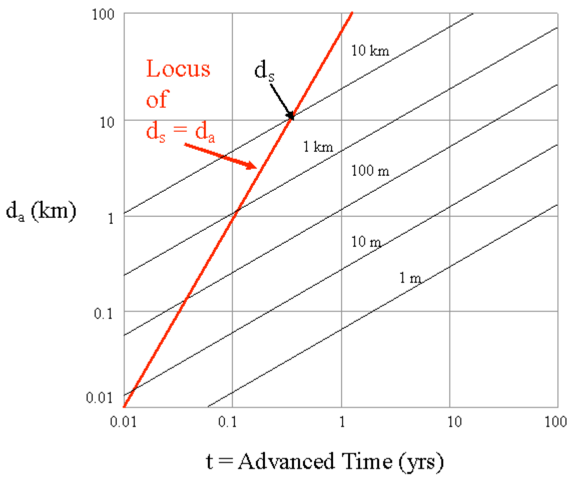
At ~10^7 sec t_{go}, v ≈ 2.6 m/sec

From Harris, v ≈ $^1/_{60}$ m/sec

Therefore:

$$\frac{TranslationalKE}{RotationalKE} = \frac{5}{2}\left(\frac{2.6}{0.015}\right)^2 > 50{,}000$$

For most circumstances, Translational KE is orders of magnitude greater than Rotational KE.



Asteroid diameter (d_a) as a function of Advanced Time (t) and solar collector diameter (d_s)
Compatible with Melosh, "Hazards… p 1119"

Conclusions:

Optimum energy efficiency uses low ejecta velocity

Despin is cheap relative to deflection

Thicker regolith may be an advantage: larger quantities of reaction mass are required for high energy efficiency

Robust design for mass driver attachment and of reaction mass processing and loading are critical

Power supply mass can be traded for mining machinery mass at a cost of lower energy efficiency

Two mass drivers, one for despin and one for velocity change may be optimal

A solar array like that used on ISS would be sufficient to deflect a 1 Km object in ten years

It is recommended that this little studied approach receive research funding. One key issue that deserves examination is the design of mass drivers which are optimized towards low velocity ejecta since these designs convert the highest percentage of the collected solar energy to momentum transfer to the asteroid.

References: [1] O'Neill, G. K. (1975) Science 190, 943-947. [2] O'Leary, B. (1977) Science 197, 363 – 66. [3] Snively, L. O. and O'Neill, G. K. (1981) Space Manufacturing 3, 391 – 401. [4] O'Neill, G. K. (1977) Astronautics and Aeronautics 16, 324 – 32. [5] Snively, L. O. (1989) Space Manufacturing 7, 246 - 251

ASTEROID 1950 DA'S ENCOUNTER WITH EARTH IN A.D. 2880. J. D. Giorgini, *(Jon.Giorgini@jpl.nasa.gov)*, S. J. Ostro, L. A. M. Benner, P. W. Chodas, S. R. Chesley, *(Jet Propulsion Laboratory, Pasadena CA 91109, USA),* R. S. Hudson, *(Washington State University, USA)*, M. C. Nolan, *(Arecibo Observatory, Puerto Rico, 00612)*, A. R. Klemola, *(Lick Observatory, Santa Cruz CA 95064, USA)*, E. M. Standish, R. F. Jurgens, R. Rose, D. K. Yeomans, *(JPL),* J.-L. Margot, *(California Institue of Techology, Pasadena CA 91125, USA).*

Initial analysis of the numerically integrated, radar-based orbit of asteroid (29075) 1950 DA indicated a 20-minute interval in March 2880 during which the 1.1-km object might have an Earth impact probability of 0.33%. This preliminary value was supported by both linearized covariance mapping and Monte Carlo methods. The dynamical models, however, were limited to gravitational and relativistic point-mass effects on the asteroid by the Sun, planets, Moon, Ceres, Pallas, and Vesta. Subsequent extended modeling that included perturbations likely to affect the trajectory over several centuries generally implies a lower calculated impact probability, but does not exclude the encounter <http://neo.jpl.nasa.gov/1950da>.

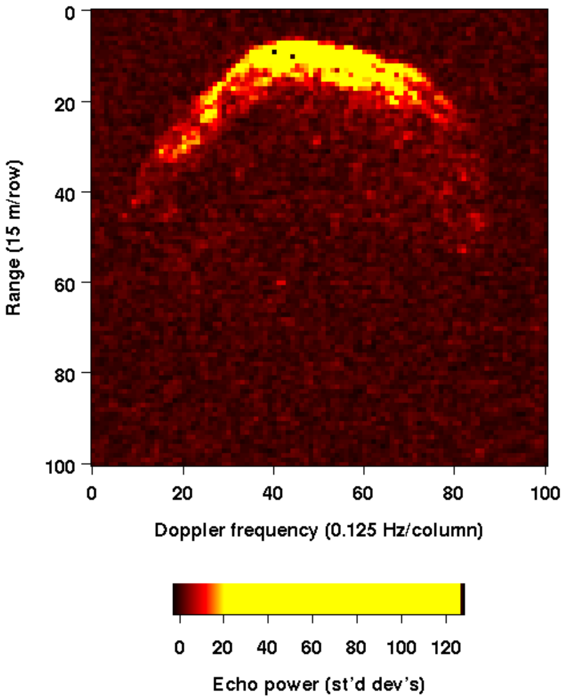


Figure 1: Arecibo (2380 MHz, 13 cm) delay-Doppler echo-power image of 1950 DA on 4 March 2001, from a distance of 0.052 AU (22 lunar distances). Vertical resolution is 15 m and horizontal resolution is 0.125 Hz (2.2 mm/s in radial velocity).

Covariance based uncertainties remain small until 2880 because of extensive astrometric data (optical measurements spanning 51 years and radar measurements in 2001), an inclined orbit geometry that reduces in-plane perturbations, and an orbit uncertainty space modulated by gravitational resonance <http://neo.jpl.nasa.gov/1950da/animations.html>.

This resonance causes the orbit uncertainty region to expand and contract along the direction of motion several times over the next six centuries rather than increase secularly on average, as is commonly the case. As a result, the 1950 DA uncertainty region remains less than 20,000 km in total extent until an Earth close-approach in 2641 disrupts the resonance. Thereafter, the same uncertainty region extends to 18 million km along the direction of motion at the Earth encounter of 2880.

Because of the quality of the dataset, we examined 11 factors normally neglected in asteroid trajectory prediction to more accurately characterize trajectory knowledge. These factors include computational noise, Galilean satellite gravity, galactic tides, Poynting-Robertson drag, major perturbations due to the gravitational encounters of the asteroid with thousands of other asteroids, an oblate Sun whose mass is decreasing, planetary mass uncertainties, acceleration due to solar wind, radiation pressure and the acceleration due to thermal emission of absorbed solar energy [Table].

Each perturbation principally alters the along-track position of 1950 DA, either advancing or delaying arrival of the object at the intersection with the orbit of the Earth in 2880. Thermal radiation (the Yarkovsky effect) and solar pressure were found to be the largest accelerations (and potentially cancelling in their effects, depending on which of two possible radar-based pole solutions is true), followed by planetary mass uncertainty and perturbations from the 64 principle perturbing asteroids identified from an analysis of several thousand.

The Earth approach distance uncertainty in 2880 is determined primarily by accelerations dependent on currently unknown physical factors such as the spin axis, composition, and surface properties of the asteroid, not astrometric measurements. Several additional conclusions are evident from the 1950 DA case.

This is the first case where risk assessment depends on the object's global physical properties. As a result of such dependency, no specific impact probability is quoted here since the results would vary with our assumptions of numerous unmeasured or unconfirmed physical and dynamic models. However, within decades, thousands of other asteroids will have astrometric datasets of quality comparable to 1950 DA's and similarly have their long-term collision assessments limited by physical knowledge. This will be a substantial change compared to the present discovery-phase, where orbit uncertainties for newly discovered objects are defined by measurement uncertainties and the time-spanned by the astrometric data.

Gravitational amplification of perturbations (due to close planetary encounters) means dynamics that are practically negligible, even over hundreds of years (including solar pressure and Yarkovsky), become factors that must be included to correctly assess impact hazard for an object having planetary encounters.

Yarkovsky accelerations require measurement since they differ significantly for each individual body, being a function of spin-pole, mass and global surface properties.

Solar radiation pressure potentially cancels Yarkovsky for one of the two most likely 1950 DA pole solutions, producing an impact scenario similar to the initial detection case. If the other pole solution is true, the two perturbations would add, delaying 1950 DA arrival such that impact in 2880 would be unlikely (Fig. 2)

	Along-track change	
Trajectory propagation factor	Distance (km)	Time
(A) Galilean satellites	-3100	-4 min
(B) Galactic tide	-8400	-10 min
(C) Numerical integration error	-9900	-12 min
(D) Solar mass-loss	+13300	+16 min
(E) Poynting-Robertson drag	-24000	-28 min
(F) Solar oblateness (J2)	[+42100, +17600]	[+49, +21] min
(G) 61 additional major asteroid perturbers	-1.5 x 10^6	-1.2 days
(H) Planetary mass uncertainty	[+1.38,-1.54] x 10^6	[+1.1,-1.3] days
(I) Solar radiation pressure	-11.2 x 10^6	-9.1 days
Combined (A-I)	**[-11.0, -17.6] x 10^6**	**[-9.0, -14.3] days**
Yarkovsky effect only	[+11.9, -71.0] x 10^6	[+9.6,-57.7] days

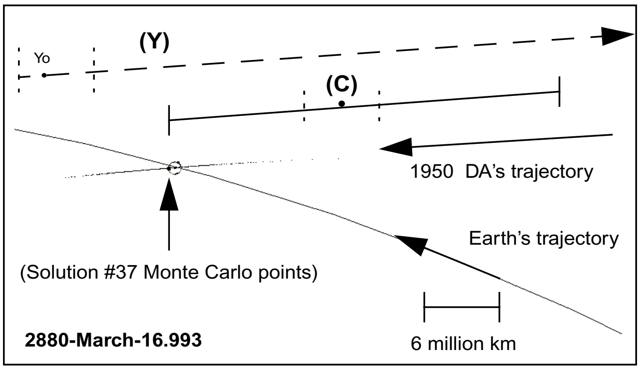


Figure 2: 500 point Monte-Carlo region from north of ecliptic plane when Earth passes through the descending orbit track of 1950 DA on 16 March 2880. Separate offset lines show possible biases caused by the Yarkovsky force only (**Y**) and then all other combined (C) perturbations. Y_o marks the result for the direct-rotation radar-pole case for the case where surface thermal conductivity is 0.1 w/mK. Vertical lines on **Y** denote the extent of variation found due to the surface thermal conductivity for that case. The vertical bars on either side of the nominal point **C** depict the Monte Carlo region along-track shift for $\pm 3\sigma$. planetary masses. A bulk density of 3 g/cc is assumed, this being the lower bound implied by the observed 2.1216 hour rotation period. This illustrates how Yarkovksy accelerations could potentially act to counter the other perturbations by advancing the 1950 DA trajectory region forward on its orbit track, as well as how manipulation of surface properties could be used to redirect (over centureies) an asteroid on an impact trajectory.

1950 DA's trajectory dependence on physical properties also illustrates the potential for hazard mitigation through alteration of asteroid surface properties in cases where an impact risk is identified centuries in advance. Trajectory modification could be performed by collapsing a solar sail spacecraft around the target body, or otherwise altering the way the asteroid reflects light and radiates heat, thereby allowing sunlight to redirect it over hundreds of years.

The next radar opportunity for 1950 DA will be in 2032. The cumulative effect of any actual Yarkovsky acceleration since 2001 might be detected with radar measurements obtained then, but this would be more likely during radar opportunities in 2074 or 2105 (or earlier if space-based systems become available). Ground-based photometric observations might better determine the pole direction of 1950 DA much sooner.

Reference: Giorgini, J., et al, *Science* **296**, 132-136 (2002).
http://neo.jpl.nasa.gov/1950da

SCIENTIFIC REQUIREMENTS FOR UNDERSTANDING THE NEAR-EARTH ASTEROID POPULATION

A. W. Harris**,** DLR Institute of Space Sensor Technology and Planetary Exploration, Rutherfordstr. 2, 12489 Berlin. alan.harris@dlr.de

Introduction: A vital prerequisite for the development of an effective mitigation strategy for hazardous near-Earth asteroids (NEAs) is a thorough understanding of their physical nature and mineralogical composition. The known NEA population contains a confusing variety of objects: there are many different "animals in the zoo" of near-Earth asteroids. Some NEAs are thought to be largely metallic, indicative of material of high density and strength, while some others are carbonaceous and probably of lower density and less robust. A number of NEAs may be evolved cometary nuclei that are presumably porous and of low density but otherwise with essentially unknown physical characteristics. In terms of large-scale structure NEAs range from monolithic slabs to rubble piles and binary systems. The rate of discovery of NEAs has increased dramatically in recent years and is now seriously outstripping the rate at which the population can be physically characterized. The NEA population is still largely unexplored.

Which physical parameters are most relevant for mitigation considerations? Preventing a collision with a NEA on course for the Earth would require total destruction of the object, to the extent that the resulting debris poses no hazard to the Earth or, perhaps more realistically, deflecting it slightly from its catastrophic course. In either case accurate knowledge of the object's mass would be of prime importance. In order to mount an effective mission to destroy the object knowledge of its density, internal structure, and strength would also be required. Deflection of the object from its course would require the application of an impulse or continuous or periodic thrust, the magnitude and positioning of which would depend on the mass and its distribution throughout the (irregularly shaped) body and on the spin vector. In either case mitigation planning takes on a higher level of complexity if the Earth-threatening object is a rubble pile or binary system.

A very important question is how remotely-sensed parameters relate to the physical properties relevant to mitigation scenarios. For instance, what can we learn about the shape, mass or structure of an asteroid from optical photometry, thermal-IR photometry, reflectance spectroscopy, radar observations, etc.? The current techniques used in the remote sensing of asteroids that are most relevant to mitigation considerations are discussed.

Optical photometry: Optical photometry is a very important source of information on the rotation rates and shapes of asteroids. Repeated observations of the rotational lightcurve of a NEA during one or more apparitions can lead to a very accurate rotation period and an estimate of the spin-axis orientation. Given sufficient resolution of lightcurve structure the basic shape of the body can be derived via lightcurve-inversion techniques [1].

A rapidly developing field in which optical lightcurve studies have played a major rôle is that of binary near-Earth asteroids. Multiple periodicity in lightcurves has been observed in a number of cases, which cannot be attributed to the effects of shape or a complex rotation state. The most plausible cause is the presence of a companion satellite or moon with mutual eclipses and occultations giving rise to extra dips in the lightcurve. Analysis of such lightcurves can reveal the period of revolution of the system and, via Kepler's Third Law, the mean bulk density of the bodies.

TABLE 1

Binary Near-Earth Asteroids

NEA	P_{rot} [h]	LC amp. [mag]	Dens. [gm cm^{-3}]	Type	Notes
3671 Dionysus	2.71	0.16	2.0	EMC?	PHA
5407 1992 AX	2.55	0.13	(2.3)	(S)	
31345 1998 PG	2.52	0.13	(2.2)	S	
35107 1991 VH	2.62	0.11	1.6	---	PHA
1994 AW_1	2.52	0.16	2.1	---	PHA
1996 FG_3	3.59	0.09	1.6	C	PHA
1999 HF_1	2.32	0.13	3.5	EMP	
1999 KW_4	2.77	0.13	2.7	Q	PHA
2000 DP_{107}	2.78	0.22	1.8	C	PHA
2000 UG_{11}	4.44?	0.10	1.5	Q,R	PHA
2001 SL_9	2.40	0.09	1.9	---	

Based on the web list of P. Pravec: http://www.asu.cas.cz/~asteroid/binneas.htm
Typical error in density ~ ±50%. PHA = potentially hazardous asteroid (MPC definition).

Table 1 lists currently known or suspected binary NEAs and the rotation periods of their primaries, lightcurve amplitudes, and densities. Bulk densities derived from binary lightcurves are generally low compared to the reference densities of the mineral mixtures of which asteroids are composed, suggestive of high porosities. Furthermore, the rotation periods are just a few hours and the lightcurve amplitudes are nearly all less than 0.2 mag. These data suggest that binary NEA primaries have significant internal cavities, rotate at a rate just below the threshold for break-up via centrifugal force of a strengthless body, and are nearly spherical in shape, characteristics indicative of consolidated rubble piles.

Recent radar observations have confirmed the presence of binary systems in the near-Earth asteroid population [2 and references therein]. The rubble-pile hypothesis offers a convincing explanation for the formation of binary NEAs: a close approach of a rubble pile to a planet may result in partial disruption of the asteroid via a sudden increase in its spin rate. A large fragment that drifts away from the rubble pile in this manner may then remain gravitationally bound to the resettled pile as a moon.

If this model of binary asteroids is correct it is vital to establish the probability that the next large Earth-threatening asteroid will be a binary rubble-pile system, since it is hard to imagine a more difficult scenario for mitigation planners to deal with. Investigating the physical characteristics of rubble piles and NEA binary systems, about which very little is known at present, and devising appropriate mitigation strategies, should be assigned a high priority on the mitigation agenda.

Since shape, rotation rate, spin-vector orientation, density, and possible binary and/or rubble-pile nature are all crucial parameters for space-mission and mitigation planning, lightcurve observations are a relatively cost-effective way of obtaining mitigation-relevant information about a large number of objects. Much can be done with 1m-class telescopes and modest CCD-cameras, although a large amount of observing time over several years is required to obtain reliable data, e.g. spin vector orientation, on some objects, depending on their lightcurve amplitudes and orbital geometries. Furthermore, accurate work on the 1-m class telescopes typically used for such observations is limited to objects brighter than V ~ 18.5. Larger telescopes are rarely used for such observations so information on the large number of small, but still potentially dangerous, NEAs with diameters less than 300m is lacking.

Reflectance spectroscopy: Spectroscopy is the main source of information on the mineralogy of asteroid surfaces. Analysis of asteroid spectra at modest resolution in the range 0.3 – 1.1 μm in terms of absorption band depth, spectral slopes, positions of maxima and minima, etc. reveals details of mineralogical composition and allows asteroids to be classed into taxonomic types according to their spectral features. Investigations of the mineralogical composition of asteroids are greatly aided by extending the spectral range into the near-infrared (e.g. to 3 μm).

Spectra of asteroids are compared with those of mineral mixtures and meteorite material to identify their most probable composition. A serious problem in the taxonomic classification of reflectance spectra is the mineralogical ambiguity of featureless spectra. Minerals such as enstatite, and other iron-free silicates, metals, and dark, organic-rich carbonaceous material all display similar relatively featureless spectra but have very different compositions and albedos. Therefore, it may not be possible on the basis of reflectance spectroscopy alone to establish whether an Earth-threatening asteroid were a massive metallic object or a fragile, porous cometary nucleus of relatively low density. Such objects would presumably demand very different mitigation approaches. In order to distinguish between the different taxonomic types giving rise to featureless spectra the geometric optical albedo of the object is required. Albedos are most often determined via a combination of optical and thermal-IR observations.

Thermal-infrared spectrophotometry: The optical brightness of an asteroid depends on the product of its geometric albedo and projected area; these parameters cannot be individually determined from optical photometry alone. If, however, observations of the optical brightness are combined with measurements of the object's thermal emission, both its albedo and size can be individually derived. The largest database of asteroid albedos and diameters compiled to date is based on thermal-infrared photometry with the IRAS satellite of some 1800 (mostly main-belt) asteroids [3].

While thermal-infrared measurements have provided the vast majority of asteroid albedo determinations to date, the extension of the thermal-infrared, or radiometric, technique to NEAs is not straightforward. Complications arise in the thermal modeling of NEAs due to their often irregular shapes, compared to observed main-belt asteroids, apparent wide range of surface thermal inertias, presumably reflecting the presence or absence of a dusty, insulating regolith (small objects may have insufficient gravity to retain collisional debris), and the fact that they are often observed at large solar phase angles.

The problem of irregular shape can be largely overcome by combining thermal-infrared observations with lightcurve-tracing optical photometry obtained at about the same time. The optical photometry allows the infrared fluxes to be corrected for rotational variability.

One approach to the thermal modeling of NEAs that appears to be successful in most cases is a modification of the so-called standard thermal model (STM) to allow a correction for the effects of thermal inertia, surface roughness, and rotation vector. The STM was designed for use with large main-belt asteroids and incorporates parameters that apply to asteroids having low thermal inertia and/or slow rotation observed at solar phase angles of less than 35° [4]. In the near-Earth asteroid thermal model (NEATM) [5] the model temperature distribution is modified to force consistency with the observed apparent color temperature of the asteroid, which depends on thermal inertia, surface roughness, spin vector, and solar phase angle. The model thermal continuum is fitted to the observed thermal-IR fluxes obtained at several wavelengths around the thermal peak in the range 5 – 20 μm. For further details see [5], [6], [7].

Given sufficient observing time on suitable telescopes, thermal-IR observations offer a means of obtaining the sizes and albedos of a significant sample of the NEA population. Since mass is proportional to diameter cubed, the size-frequency distribution of the NEA population is of critical importance to the impact-hazard issue. Since asteroids have albedos, p_v, ranging from a few percent to about 60%, measurement of absolute brightness (H-value) alone allows the diameter to be determined to an accuracy no better than a factor of 2, and the mass to an accuracy no better than a factor of 8.

In order to be able to interpret the number/H-value distribution of the NEA population in terms of a size-frequency distribution, the albedo distribution is required [8]. There is some evidence of a size-dependency of asteroid albedos that might reflect the effects of space weathering [6], [9]. Collisional fragments from the break-up of larger bodies would be younger and therefore have had less exposure to space weathering and thus have brighter surfaces. Continuous collisional processing may therefore give rise to a general dependence of albedo on size. In the case of NEAs the effects of space weathering, or rather the lack of it, may blur the albedo/taxonomic class associations familiar from studies of main-belt asteroids and complicate the interpretation of reflectance spectra in terms of mineralogical composition. For these reasons, the study of NEA albedos is of crucial importance to NEA impact-hazard and mitigation considerations.

Radar observations: Radar is a very powerful technique for investigations of NEAs, not only for astrometric purposes but also for obtaining information on their sizes, shapes, and surface properties. Given adequate signal/noise so-called "delay-doppler" images of objects can be constructed that can show small-scale structure such as craters on their surfaces. However, due to the inverse 4^{th}-power dependence of echo strength on distance, delay-doppler imaging is restricted to those NEAs making very close approaches to the Earth. Radar results have revealed that NEAs have shapes ranging from almost spherical to very elongated and irregular and have recently confirmed the existence of NEA binary systems [2].

The use of radar in the framework of NEO hazard assessment and mitigation is described in detail elsewhere in these proceedings. For the purposes of the present discussion we note that results from other observing techniques can greatly assist the interpretation of data from radar investigations and vice versa: The analysis of radar data is aided by the results of lightcurve observations, which can provide valuable input on spin vectors and shapes for the radar modeling. Radar observations combined with optical lightcurve data often provide independent constraints on asteroid sizes for comparison with diameters obtained from infrared spectrophotometry (see above). The comparison of optical and radar albedos provides insights into the nature and composition of asteroid surfaces.

Summary and Discussion: A wealth of information on the mitigation-relevant physical properties of large numbers of NEAs can be obtained from the diverse observing techniques available at Earth-based observatories, as summarized in Table 2.

TABLE 2

Summary of Mitigation-Relevant Information Obtainable from Earth-Based Observations of NEAs

Optical photometry (lightcurves)	Reflectance spectroscopy	Thermal-infrared spectrophotometry	Radar
• Rotation rates • Shape estimates • Spin-axis orientation • Identification of binaries • Densities (from modeling of binary-system lightcurves)	• Mineralogical composition	• Sizes • Optical geometric albedos (p_v) (composition) • (Future: thermal inertia; mineralogical composition from wavelength-dependent emissivity?)	• Accurate astrometry • Sizes • Radar albedos (composition) • Shapes • Identification of binaries (densities)

Progress in this endeavor is limited, however, by the restricted access to the relevant telescopes due to the observatories' observation-proposal review procedures, which are designed to maximize overall *scientific* return in astronomy in general and do not, at present, make allowance for the special circumstances of the NEA hazard assessment/mitigation task.

An important aspect of the application of astronomical remote-sensing techniques to the investigation of NEAs is the *interdependency* of the various techniques described above for the interpretation of observational data. A comprehensive understanding of the nature of NEAs requires a combination of virtually all observing techniques available. Rendezvous missions can provide "ground truth" for a few objects and thus aid in the accurate interpretation of Earth-based remote-sensing data, but for a thorough understanding of the diverse physical characteristics of the overall population of NEAs, which is vital for the development of an effective mitigation strategy, collaborative international Earth-based observation programs are essential.

References: [1] Kaasalainen M. et al. (2002) in *Asteroids III,* (W. Bottke et al. eds.), pp. 139-150. Univ. Arizona Press. [2] Margot J. L. (2002) *Science, 296*, 1445-1448. [3] Tedesco E. F. (ed.), (1992) *Tech. Rep. PL-TR-92-2049*, Phillips Lab., Hanscom Air Force Base, MA. [4] Lebofsky L. A. et al. (1986) *Icarus, 68*, 239-251. [5] Harris A. W. (1998) *Icarus, 131*, 291-301. [6] Harris A. W. and Lagerros J. S. V. (2002) in *Asteroids III,* (W. Bottke et al. eds.), pp. 205-218. Univ. Arizona Press. [7] Delbo M. and Harris A. W. (2002) *Meteoritics and Planet. Sci*., in press. [8] Werner S. et al. (2002) *Icarus, 156*, 287-290. [9] Binzel R. P. et al. (2002) in *Asteroids III,* (W. Bottke et al. eds.), pp. 255-271. Univ. Arizona Press.

Speed limits of rubble pile asteroids: Even fast rotators can be rubble piles. K. A. Holsapple, University of Washington, Box 352400, Seattle, WA 98195 holsapple@aa.washington.edu

Introduction: (At the mitigation conference, my presentation included two topics: the observations that support many asteroids having a rubble pile structure, and the implications of that on mitigation scenarios. This is a summary and some recent extensions of the first topic: on the spin states of asteroids. The second topic is reported separately.)

The spin states of asteroids are limited by the internal stresses produced by the centrifugal forces due to spin. An oft-quoted result ([1] and others) is that a rubble pile, strengthless material can not have a period less than about 2.1 hours (11 rev/day maximum). Faster spins produce centrifugal tensile forces at the equator greater than compressive gravity forces, so material would be flung off. That analysis was for spherical bodies, and [1] suggested a linear reduction of maximum spin with increasing aspect ratio for elongated bodies.

A plot shown by several at the conference is shown in figure 1 (This version was obtained from the website of Petr Pravec. See also [2])

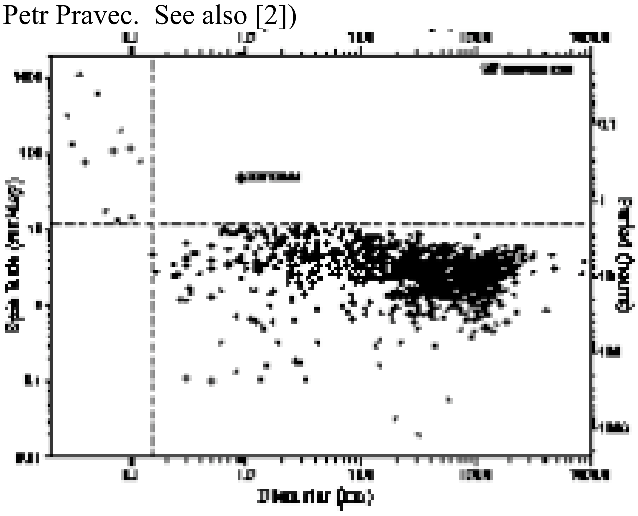


Figure 1. Spin versus size of asteroids. The speed limit of 11 rev/day is shown by the horizontal dashed line. The dozen asteroids at the left with diameters less than 150 meters have spins up to 100 times that limit, they are called the 'fast rotators'. The recently discovered asteroid 2001QE84 is the first larger asteroid with a spin above the limit.

It presents the data of spin rate versus diameter for about 1000 asteroids. This plot has two features that should be noted. The first is the fact that, indeed, all asteroids larger than 1km (and all except one larger than 150m) are below the critical spin limit. This is taken as a major indicator of their possible rubble pile structure. Second, all recently discovered asteroids less than 150m in diameter have spins significantly in excess of that speed limit. Those must have some cohesion, and they are often referred to as 'monolithic rock fragments'.

The strength of asteroids is an important property for all dynamical processes involving evolution, disruption, cratering and mitigation methods. Thus, what do these spin observations tell us about the strength and internal structure? What bounds do they give? The answer can be obtained by a detailed study of the complete three-dimensional stress state induced by a given shape and spin. This is a report on an analysis of that spin data, and a comparison of the data with new analyses of the internal stress states introduced by the spin of asteroids.

History. Considerations of the stresses in bodies with gravitational forces and spin date all the way back to Newton, 1687, who first considered the equilibrium shape of the Earth. He made the very simplifying assumption that an oblate earth could be analyzed as a fluid. Later studies by Maclaurin, Jacobi, Roche, and Poincare continued along the same lines: limiting the analysis to fluid bodies, but considered a variety of ellipsoidal shapes.

More recent studies have assumed linear elastic bodies, and have determined the internal stress state for arbitrary ellipsoidal bodies with spin. Then, after the elastic analysis, an additional assumption is required about the strength model, and different strength models give different results. An important and often overlooked limitation of these approaches is an implicit assumption that removal of the gravity and spin forces would return the body to a state with zero residual stresses. That assumption is unlikely to be valid considering the complex history of asteroid formation and environment.

The spin limit of [1] and others considers the uniaxial forces only, and not the actual three-dimensional stress state. Therefore, it was known that it provided only an estimate of the actual limit.

Limit Stress States: A more general approach [3] considers complete 3D stress states, and limit states without the need to consider the history of stress and internal residual stresses. While the stresses in a body due to given loads depends upon the stress-strain behavior of the material, the limit stresses of an elastic-plastic body do not depend on the intervening stress-strain behavior. That feature is at the heart of the so-called limit analysis methods of plasticity theories. For that reason, limit stress states can be derived without consideration of possible residual stresses, or of the stress-strain behavior below the limits.

The analysis in [3] determines the stresses in a spinning, cohesionless ellipsoidal body at the limit spin states. While the cohesion is zero, the 'strength' is most certainly not zero. The model is that of a Mohr-Coloumb material, in which the maximum shear stresses increase linearly with the pressure, the coefficient being determined by the so-called 'angle of friction'. Thus, the 'strength' is not zero under non-zero confining pressure. This is the model most commonly used for geological materials.

In general, the speed limits obtained are functions of both size and shape, so a plot of the spin limits would need to be plotted as a function of both. The figure 1 shown above is a projection into the spin-size plane of such a 3D plot. However, for the cohesionless case, the results are independent of asteroid size, so the meaningful plot is the maximum spin versus the ellipsoidal aspect ratio, for various values for the 'angle of friction'. Assuming a prolate body for simplicity, for which the two smaller diameters are the same, figure 2 shows the limit spin states determined by the analysis, as well as asteroid data.

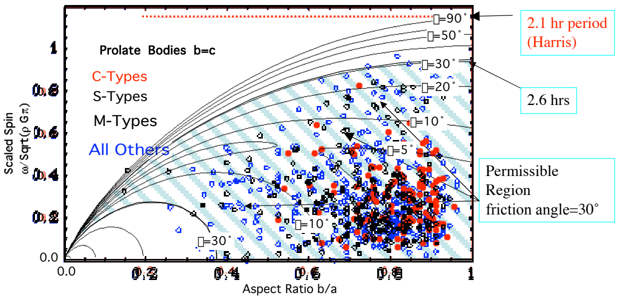


Figure 2. Limit spin states for a cohesionless Mohr-Coloumb ellipsoidal body, for different angles of friction. The highlighted region shows the permissible states for an angle of friction of 30˚. Superposed are the data for about 800 asteroids segregated into four taxonomic groups. These are the larger asteroids only, the recently discovered small fast-rotators are off this curve at the top. It is seen that almost all of these large asteroids all are within the spin limits determined.

The one-dimensional spin limit estimate of [1] is shown at the top right. The complete analysis is seen to lower this limit, with now a minimum period of 2.6 hours for a spherical body, reducing to a minimum period of about 5 hours, for very elongated bodies, with a diameter ratio of 4 or 5 to 1. However, although the new analysis is much more refined, the bottom-line conclusion is little changed. That is, the data of almost all larger asteroids are within the limits imposed by a cohesionless body. That suggests, but does not prove, that the larger asteroids are indeed rubble piles.

Fast Rotators: Now, what about the "fast rotators"? While they clearly must have cohesive strength, how much is required? I have since the conference just completed an analysis extending that of [3] to include both cohesion and friction components of strength. The complete analysis will be in a forthcoming paper, but results are presented here.

In this more general case the results for maximum spin depend on both shape and diameter, so can be plotted in two ways. Assuming a spherical shape, the limits depend only on size. These limits as a function of diameter are shown superposed on the above plot in figure 3:

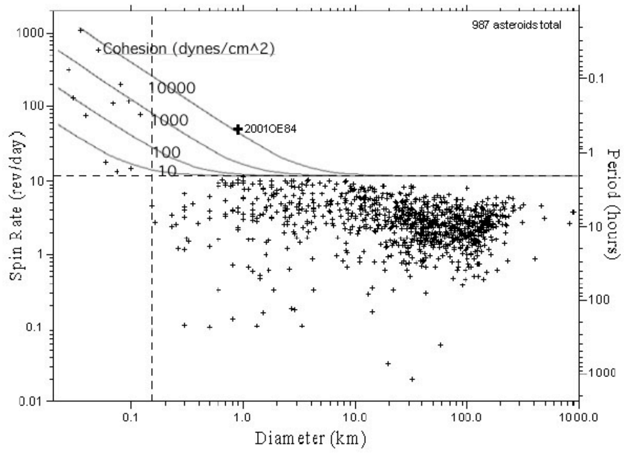


Figure 3. Spin limit curves for spherical asteroids as a function of size for a cohesive, Mohr-Coloumb material with different values for the cohesion and an angle of friction of 30˚. The Pravec data for actual asteroids is superposed. The fast rotators are the dozen points at the upper left.

These results are very interesting. First, note that, just as for impact cratering, there are two regimes. For the larger asteroids, the cohesion is of no consequence for the range of cohesion considered here. The 'strength' of these asteroids is a result of the angle of friction and the gravitational compressive pressures. Further, there is no size dependence in this "gravity regime". Then, for the smaller asteroids in which the gravitational pressures are small, the results depend only on the cohesion, in what can be called a "strength regime".

Even more important, note the cohesion required for the fast rotators. A cohesion of only 10^4 dynes/cm^2 is all that is required for the observed spins. While an elongated body requires a little more strength, a value of, say, a few times 10^4 dynes.cm^2 is sufficient to hold all of these bodies together! A sample of a material with a cohesion of only 10^4 could not even withstand terrestrial gravity without collapsing if it were over 5 cm in height!

This result shows that calling these bodies "monolithic" and "shards" and "rocks" is not warranted from the actual data. Statements in the literature referring to the asteroids smaller than a few hundred meters in diameter as "intact, internally monolithic bodies that retain the tensile strength to rotate at such extreme rates" cannot be defended. Instead, these small asteroids might also be rubble pile bodies, with only an almost negligible strength. A Mohr-Coloumb model with a cohesion of a few times 10^4 dynes/cm^2 gives a bound on spin that is clearly above all observations, and smoothly connects the data from the small to the large asteroids.

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The Deflection of Menacing Rubble Pile Asteroids. Keith A. Holsapple, University of Washington, Box 352400, Seattle, WA,98195 (holsapple@aa.washington.edu).

Introduction: For a couple of decades now, researchers have taken seriously the notion that impacts on the earth of large asteroids or comets has occurred in the past, and will, without active intervention, occur again; with devastating affects on the earth and all living creatures. About ten years ago, researchers [1,2,3] suggested and studied a number of ways that an asteroid could be diverted from an impending collision with the earth by pushing it sufficiently to change its course, making it miss the earth.

The methods envisioned included the use of nuclear explosives, the impact by large masses at high velocities, the blowing off of material by either the concentration of solar energy using giant mirrors or by zapping it with lasers, and more mundane methods such as simply attaching a propulsion device or throwing dirt off at sufficient velocity to escape the asteroid. Among the methods suggested, it is generally accepted that with only a very short warning time, such as a few years, only the nuclear bomb approach would work.

The analysis of the various methods relies on data accumulated for cratering, disruption and material properties of terrestrial materials. In most cases those are for silicate materials with mass densities of 2-3 g/cm^3. However, it is becoming generally accepted that many of the asteroids are re-accumulated rubble pile bodies of very low density and strength. The comets are certainly thought to have that structure. Therefore, I report here some initial studies of the effects of a low-strength porous structure on the various mitigation methods.

Background:

Modeling of porous materials. Various models of the thermodynamical behavior of porous materials were developed several decades ago, in response to interest in porous materials as a method to protect weapons systems from the damaging influences of the x-ray deposition from nuclear bombs. One of the most used is the "p-alpha" model developed by Walter Herrmann at Sandia. It is a component of the Sandia WONDY and CTH wave codes which are used by many in the planetary impact community.

The mechanical behavior of the model is essentially the same as an elastic-plastic model, but for the dilatational (pressure-volume) component, not the deviatoric shear component of plasticity theories. The model assumes that the material is comprised of small particles of normal 'solid' density ρ_{solid} (say about 3 g/cm^3) separated by intervening pore spaces. That gives a net mass density of a lower value ρ_{porous}. The ratio $\rho_{solid}/\rho_{porous}$ is the parameter α, the distension ratio . Then, as pressure p is applied, the material permanently crushes to a larger density as the pores collapse. That crush behavior is defined by a curve of α versus pressure p. If the pressure is removed, there is a small elastic recovery, but no change in the permament crush.

The thermodynamic assumptions are that the internal energy is contained in the solid particles, so that the energy per unit mass of the solid particles and the porous material are the same. The pressure of the porous material is a factor $1/\alpha$ of the pressure of the solid particles.

Inherent in this model is the assumption that this crush behavior is instantaneous. That is a consequence of the assumption that the particles are small, so that the time scale of pressure equilibrium of the particles is negligible compared to time scales of a problem. For larger particles, this model would not be appropriate.

Experiments in porous materials. Few experiments have been made of impacts into highly porous, low strength materials. There are those reported in [4] for moderately porous materials, and, more recently, those by Housen [5] and Housen and Holsapple [6], and those by Dan Durda [7] in highly porous materials. One should note the wide range of results these investigations produced, because there are many different types of 'porous materials'. In [4], the results by Shultz are not different in nature from those for conventional materials: craters form primarily by excavation. Shultz assumes that conventional gravity scaling defines extrapolations to low gravity. In [6] craters are also formed, but mostly by compaction, not by excavation. Strength scaling is found for low gravity. Durda, in [7] shoots projectiles entirely through open-pore foam materials with no cratering at all, but at an impact velocity lower than those of interest.

Consequences for mitigation: The effects of porosity are primarily due to a very low strength, and due to the energy absorption properties of a crushable material. For that reason, there is little affect on the 'low force, long time' methods such as mass drivers and propulsive methods. The only issues for those methods would be the difficulties of anchoring devices on a very low strength regolith. The focus here is on the impulsive methods, which are discussed in turn.

Impact Methods. The deflection of an asteroid by an impactor is a result of the momentum transferred to the target asteroid by the impact of a mass at a high velocity, several tens of km/sec. The velocity of the asteroid need change by only a few cm/sec to make it miss the earth, if it is done a decade or so before an impending impact with the earth [1]. For an impact into most materials, a large amount of ejecta is thrown out as a crater forms. Some of that ejecta will re-impact the asteroid, and some will escape into space. There is no net change in momentum of the asteroid from the ejecta that re-impacts, but there is a contribution from the ejecta that escapes. Further, on a 10 km asteroid the escape velocity is only a few m/s, so most of that ejecta escapes. Thus, the total momentum change of the target asteroid is that of the impactor, plus that of the ejecta that escapes.

The momentum transferred from the impactor is simply its mass *m* times its velocity *U*. The most direct way to calculate the momentum of the ejecta is from a plot from experiments of the velocity of the ejecta versus the mass of that ejecta. The figure 1 shows such a plot, it is a scaled plot of the mass of ejecta with speed greater than a velocity *v* versus that velocity *v*.

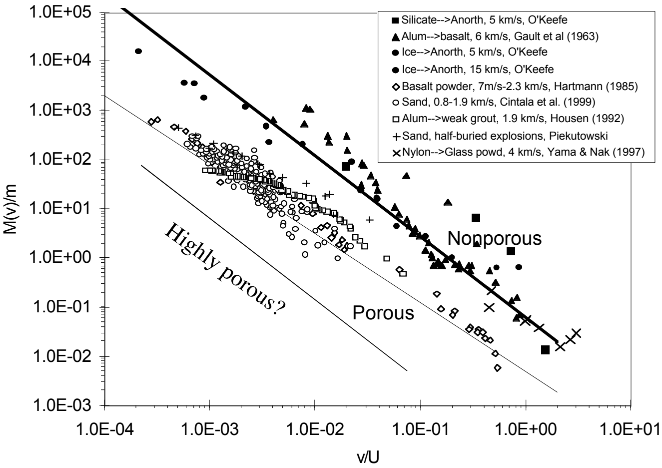

Figure 1. The mass of ejecta with velocity >*v* as a function of *v*, from experiments and calculations. The ordinates of the points at the left approach the total crater mass due to excavation. Plotted in this scaled way, the data for all non-porous materials are on one curve, and the data for the moderately porous materials on another. Results for velocities for very porous materials have not been obtained, but the component of excavation has been determined to be very small for those materials [4]. A possible line for those materials is also indicated.

Without describing the details, the momentum of the ejecta can be determined from this plot. For the curve labeled 'non-porous', the result is about *13 mU*, or *13* times the momentum of the impactor. (The fact that impacts into non-porous materials impart a momentum change that is many times that of the impactor is called 'momentum multiplication') On the other hand, for the curve labeled 'porous' the result is only *0.2 mU.* Adding back the impactor momentum, the total momentum change of the asteroid would be, in these two cases, *14 mU* and *1.2 mU*. Obviously, for an even higher porosity target, the momentum of the ejecta becomes of no consequence, and only the momentum *mU* of the impactor is transferred to the asteroid. This is a what is called a 'perfectly plastic' impact.

A direct consequence of this result is that, without the momentum multiplication factor of *14*, the mass required to change the velocity of an asteroid by *10 cm/sec* for a given impact speed increases by a factor of *14.* In [1,2,3] the mass required to deflect a *1 km* asteroid with an impact velocity of *10 km/s* is estimated to be from *200* to *1500 tons*. The integration of the upper curve of figure 1 gives *700 tons*. Then, for a porous asteroid, these masses get multiplied by a factor of *14,* to give a requirement of about *10 kt* mass, an unreasonably large number to deliver to the asteroid, at least for a single impact.

Surface or subsurface Nuclear Exposions. I know of no calculations or experiments for explosions in highly porous materials. While there are numerous experiments for cratering by explosives in dry sands, those sands do not have the low crush strength that produces large compression craters and the small amounts of ejecta compared to the highly porous materials. However, there are experiments for impacts into low strength, highly porous materials [6], and it is commonly thought that there is a close analogy between impacts and explosives buried a small distance under the surface. Therefore, as a crude estimate, the explosive methods might also be decreased in efficiency by a factor of *15* or so. In [1] it is determined that to deflect a *1 km* asteroid by a surface-burst nuke would require a *90 kt* device. If this is increased by a factor of *15*, it would then require a megaton device for a *1 km* asteroid, and a gigaton device for a *10 km* asteroid. A gigaton in a single device is larger than ever developed, and larger that most would think is prudent to develop. Clearly, much more analysis and experimentation is needed for explosions in porous materials.

Standoff nuclear explosions. There is doubt about energy deposited directly into an asteroid, because of the possibility of splitting it into two or more parts, which then still might impact the earth. Consequently, it has been suggested to use a nuclear explosion at some distance from the asteroid. The energy from the device, largely in the form of x-rays and neutrons, streams out to intercept the surface of the asteroid, heating a surface layer a few tens of cm thick almost instantaneously. That heated material will then expand, and, if it has little strength, will be blown off the surface into space. That imparts a momentum to the asteroid.

I have used the WONDY code with the p-alpha model to calculate the amount of momentum for both porous and non-porous materials. There is a dramatic change when the porosity and low strength are included. I revisited the case favored in [1] with a standoff distance of *0.4* times the asteroid radius. For a *1 km* asteroid, that required a device with a yield of

100 kt to *1 Mt*. The heated layer is *20 cm* thick, which, assuming a uniform energy deposition, attains an initial specific energy of *2* 10^9 *ergs/g*, well below the melt or vaporization energy of silicates. (For an asteroid with porosity, that depth is increased to include the same amount of heated mass.) For a solid material, the resulting pressure is about 10^{10} *dynes/cm*^{2} or *10 kbars*. However, at that same specific energy in a material with porosity, the pressure is reduced to only the crush pressure of 10^7, or *10 bars*. That factor difference in pressure of *1000* reduces the momentum imparted by the blowoff by a factor of *1000*. Therefore, the predicted change of velocity of *10 cm/s* by that device is reduced to only a negligible *0.01 mm/s*. Conversely, the device required for deflection using the standoff mode is increased by a very large factor, which would likely become unreasonably large.

This reduction in effectiveness is a direct consequence of the magnitude of the pressure that the heated layer develops when it is heated. That pressure, multiplied times a time interval equal to a transit time for a wave to travel across the heated layer, times the area of heated material, is the momentum transferred to the asteroid.

Figure 2 shows the pressure developed as a function of the energy per unit mass deposited into a heated material, both for a conventional solid material and for p-alpha porous materials. At the specific energy of *2* 10^{10}, the porous curves are about a factor or *1000* less than the solid curve, resulting in that *1000:1* reduction in transferred momentum.

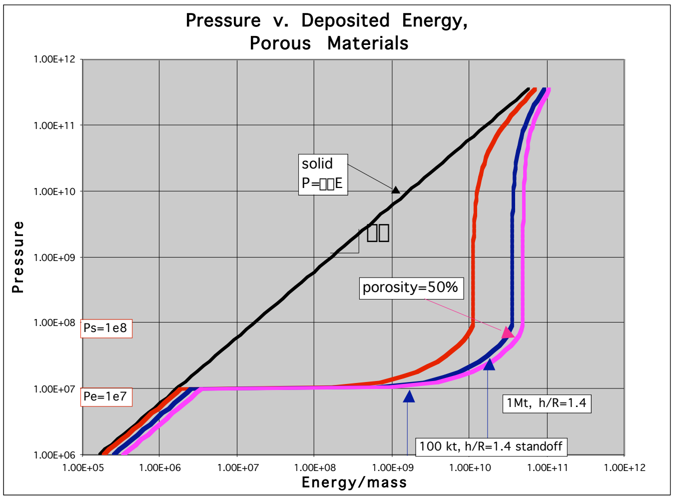

Figure 2. The pressure in a material instantaneously heated to a given energy per unit mass. Curves are for a solid material, and for porous materials with different porosity . It is assumed that crushing begins at a pressure of 10^7 dynes/cm^2 and is completed at the pressure of 10^8.

The physical reason for this large effect can be described. When a porous material is heated to give a pressure above its crush pressure, the solid particles can, according to the p-alpha model, instantaneously expand into the pore space. Even a pore space that is *10%* of the volume will allow the solid particles to expand by *10%.* A change of density of *10%* in a solid gives a reduction in pressure of *10%* of the bulk modulus, which is on the order of several times 10^{11} *dynes/cm*^{2}. Therefore, the reduction in pressure is on the order of 10^{10} *dynes/cm*^{2}, or to the crush pressure, whichever is greatest. That is almost all of the pressure originally in the solid particles. It is noted that the important property leading to that large reduction in pressure and transmitted momentum is not especially the porosity, but the crush pressure. In a material like a dry sand, the crush pressure is on the order of 10^9 so this effect is still present, but reduced to a factor of *10* or so.

Laser and concentrated solar heaters. These methods also rely on the heating of surface material with resultant blow-off and momentum transfer. However, they are different from the case of a nuclear standoff explosion in that the time scales of energy deposition may be longer, the penetration depths much more shallow, and the specific energies are high enough to vaporize material. Unfortunately, the only calculations and experiments are again for non-porous and strong materials. For example, in [2] are reported experiments using a high-powered laser focused on a basalt target. Again, I know of no experiments or calculations in highly porous materials, but they could be done fairly easily. Thus, much more analysis and experimentation needs to be done before we can consider these methods to be viable.

Summary: Porous, low-strength materials are very effective at absorbing energy. That is why they are used for packing materials and for protection from impacts. They were contemplated during the cold war as a way to protect weapon systems from x-ray deposition from nuclear weapons. It should therefore come as no surprise that it is hard to divert a porous asteroid or comet. From the estimates derived here, all of the short-time, large-impulse methods may be of questionable effectiveness. Even for a non-porous asteroid, the presence of a low porosity regolith only a few cm deep could lead to these same problems. That leaves the low force, long time methods. However, even in those cases the problems of anchoring devices to the surface may make them very difficult. If a 10 km asteroid with our name on it is discovered in the next few years, there is no method contemplated that will surely work to divert it.

A focused program of synergistic laboratory experiments and code calculations could clarify the questions raised here. Missions to asteroids and comets can determine more about their actual structure, if their surface is poked or impacted. Such progrmas must be a component of larger programs to study the issues of the mitigation of the effects of large body impacts into the earth.

There is much research to be done. "We knew a lot more about asteroids 10 years ago than we do now" [8].

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[8] A quote from Don Yeomans (2002).

THE SCIENTIFIC REQUIREMENTS OF FUTURE MITIGATION TECHNOLOGY. R. Kahle[1, 2] and Ch. Gritzner[2], [1]German Aerospace Center, Institute of Space Sensor Technology and Planetary Exploration, Rutherfordstrasse 2, 12489 Berlin, Germany, ralph.kahle@dlr.de, [2]Dresden University of Technology, Institute for Aerospace Engineering, Mommsenstrasse 13, 01062 Dresden, Germany, christian.gritzner@mailbox.tu-dresden.de.

Introduction: Currently, various ideas for the diversion and/or disruption of hazardous asteroids and comets exist. Among them are systems that might be technologically feasible at present, such as chemical rocket engines, kinetic energy impacts, and nuclear explosives. Others are currently under development and might be possible with some effort, e.g. solar concentrators and mass drivers. Some systems seem to be too far off to be realized in the required size for the task of NEO deflection within the next decades, such as solar sails, laser systems, and the utilization of the Yarkovsky effect. Besides, there are also futuristic technologies such as eaters, “cookie cutter”, and the use of antimatter. The use of solar sails would probably demand for large and heavy mechanical structures and might thus never become a realistic mean for mitigation. The same can be expected from the utilization of the Yarkovsky effect, e.g. covering an object with dirt. Further, the interaction of kinetic energy impacts or nuclear explosives strongly depends on the interior structure of the object. Here, two mitigation concepts will be discussed that could become attractive alternatives in the mitigation of hazardous objects: the solar concentrator and the mini-magnetospheric plasma propulsion.

Mitigation Strategies and Techniques: Generally, mitigating the impact hazard could be either done by deflecting the threatening object from its collision course or by destroying the object itself. In case of NEO deflection one can further distinguish between the long-term application of a continuous small thrust, and the sudden application of a large impulsive thrust. In the first case, the NEO would be propelled for a period of several months. Ideally, the force would be applied through the objects center of mass parallel or anti-parallel to its velocity vector, which would increase or decrease the semi-major axis of the NEO orbit. Thus, the arrival at the intersection point with Earth’s orbit would be delayed or advanced respectively. This kind of orbit alteration could only be applied if sufficient warning time in the order of magnitude of a decade is given. Here, one could possibly deal with solar concentrators, attached thrusters, mass drivers, or lasers.

If a lesser time is available, the orbit has to be changed rapidly. Dealing with the worst case we would have to apply our mitigation means in the very last orbit before the collision. Here, the correction force should be applied in an almost perpendicular direction with respect to the NEO velocity vector [1]. The only possible means for conducting such a high-energy interaction would be either nuclear explosives or kinetic energy impactors. For both techniques the danger of an uncontrolled fragmentation of the NEO has to be considered. The size of the fragments that remain on a collision course with the Earth is a critical factor. Only fragments smaller than some 30 m burn up in the atmosphere. Larger objects could penetrate the atmosphere and if many, could cause a series of impacts over large territory (firestorm).

Scientific Requirements: All the mitigation techniques mentioned above have in common that they require specific knowledge of the target object. For an efficient application of any mitigation technique the dynamic properties of the object must be known, e.g. orbit, albedo, size, shape, mass, and state of spin. This data is generally gathered by means of remote sensing, including measurements by ground-based and Earth-orbiting telescopes, or spacecraft flyby and rendezvous missions [2]. When dealing with high-energy interactions, such as surface and sub-surface nuclear explosions or kinetic energy impacts, the interior structure of the object will dramatically affect the efficiency of the interaction. Porosity (rubble pile structure or porous regolith) could decrease the efficiency of a kinetic energy impact and a surface nuclear explosion by a factor of 5 and 100 respectively [3]. To gather the relevant information about the interior, precursor missions are mandatory. Seismic investigations would reveal material strength parameters for dense objects such as metallic or stony asteroids. On the other hand, radio tomography could detect the state of fracture. However, if we cannot gain the required interaction data, short-term deflection methods would imply a very high risk and a low probability for a successful diversion maneuver.

Thus, the necessity of conducting short-term deflection missions has to be reduced. The best effort would be an intensified search for NEOs down to 100 or 200 m. Since these small objects are both, more numerous and fainter than the 1 km NEOs of NASA’s current goal, such a survey would last several decades. In the meanwhile we cannot rule out the possibility of an Earth impact. This situation demands for a simultaneous physical characterization of NEOs and an analysis of suitable mitigation technologies along with the surveys. In the following, two mitigation options will be discussed, which could become of importance for means of mitigation and exploration as well. The first technology is a solar concentrator, which could be used to analyze surface properties of NEO's and to demonstrate deflection capabilities at the same time. The second system could be of importance for both reconnaissance and mitigation: the mini-magneto-spheric plasma propulsion.

Solar Concentrator: The application of solar concentrators for NEO mitigation was discussed first by Melosh et al. [4]. The basic idea of this technology is to concentrate solar radiation onto the NEO surface with a lightweight (parabolic) reflector (figure 1). Depending on duration and intensity of illumination, the material within the spot will be heated up and vaporizes. The evaporated material accelerates to a speed of about 1 km/s and delivers an impulse to the NEO. Although the generated thrust is small (tens to hundreds of N) it will suffice to deflect the NEO from its collision course with Earth if sufficient lead-time is given (years). Such a system could be operated for the duration of several months, which would lead to a slight increase in semi-major axis of the PHO when the thrust vector is aligned with the orbital velocity vector of the NEO.

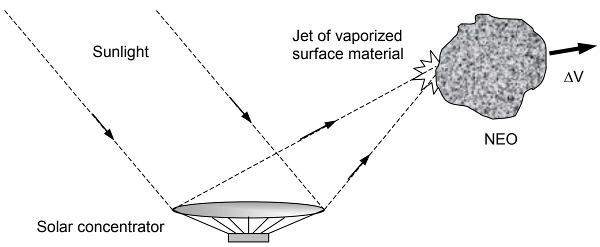

Fig. 1: Working principle of solar concentrator.

Physical Processes: The following equations and numbers are applicable for a parabolic solar collector. Simplified equations for the estimation of vapor production rates and thrust are adopted from Melosh et al. [4]. Here, the mass flow rate dm/dt of the ejected material is given by the light intensity P divided by the heat of vaporization H, which is a function of the thermodynamic properties of a specific material. H values have been derived from meteorite data given in Remo [5] and are summarized in table 1. Note that the data was gathered under terrestrial conditions (atmospheric pressure). Melting and boiling points might differ for vacuum conditions.

The vaporization energy for water ice is assumed as H = 3 MJ/kg [4]. Further, the ejection velocity v is supposed to be the molecular speed of vapor molecules (> 1 km/s). Finally, the generated specific thrust F [N/m^2] normal to the NEO surface is given as the product of vapor mass flow rate dm/dt, ejection velocity v, and a numerical factor $\beta = 0.5$ that accounts for a hemispherical spread of the vapor: $F = \beta*(dm/dt)*v = \beta*v*P/H$. The light intensity P is a function of the solar constant $S = 3\ 10^{25}$ W at a distance R from the sun, the diameter of the solar mirror D_{mirror}, the spot diameter D_{spot} and the reflectance ψ (about 0.85 for aluminum-coated foils): $P = S*\psi*D^2_{mirror}/D^2_{spot}/R^2$.

	Stony meteorites	FeNi meteorites
Melting point	1350…1800 K	1770 K
Boiling point	2960 K	3510 K
Average specific heat	900 J/kg/K (s) 1100 J/kg/K (l)	< 700 J/kg/K (s,l) < 400 J/kg/K (g)
Heat of vaporization	6.05 MJ/kg	6.4 MJ/kg
Heat of fusion	0.27 MJ/kg	0.27 MJ/kg
Estimated energy for vaporization	9.3 MJ/kg	9.1 MJ/kg

Tab. 1: Thermal properties of stony and FeNi meteorites, according to [5].

Melosh et al. examined the influence of the light intensity on the start-up time for evaporation [4]. They found that this time t increases for decreasing intensities P as $t \sim P^{-2}$ (e.g. 10^{-4}s for 10^9 W m^{-2} and 1 s for 10^7 W m^{-2}). This has to be taken into account when dealing with NEO's where the surface constantly moves beneath the spot depending on the NEO rotation period, the spot latitude, and the NEO shape. This performance is also strongly influenced by the thermal conductivity of the surface material. Here, the difference between stony (1.5 to 2.4 W/K/m) and iron-nickel asteroids (about 40 W/K/m) becomes obvious. Simple numerical computations affirmed the dependency that was found in [4]. As a result, a 200 m diameter collector (at 1 AU sun distance and 1 km distance towards the asteroid) would vaporize surface material of a stony asteroid within 3.5 to 7.5 minutes (lower limit: ρ=2g/cm^3, λ=2W/m/K and upper limit: ρ=3.8g/cm^3, λ=2.4W/m/K). The vaporization process for a metallic object would take about 2 to 3 hours (ρ=4.7g/cm^3, λ=40W/m/K and ρ=7.7g/cm^3, λ=40W/m/K). Extending the concentrator to 500 m diameter these start-up times for vaporization of metallic objects would reduce to 200 and 300 seconds respectively. This shows the importance of the thermal properties of the objects surface. Considering objects with regolith layers, the thermal conductivity would be further reduced. Thus a regolith layer would increase the concentrator performance.

Concentrator Properties: Focusing solar radiation onto a spot on the surface of a NEO can be done in two ways: by reflection or refraction. For refraction a Fresnel lens could be used, which may consist of a lightweight polymer foil with engraved concentric refracting rings. A reflecting solar collector could be either a large parabolic mirror or an array of small parabolic or plain facets. A typical value for the reflectance is 0.85 for aluminum-coated foils. Higher values of up to 0.95 are technically feasible.

When operating a solar collector system close to a NEO the pointing accuracy is an important issue, because of the orbital movement of NEO and collector system towards each other, as well as the NEO rotation. Due to the generally non-spherical shape of the NEO and the properties of the collector surface, focusing mismatches will occur that have to be considered in advance in the system layout. A disadvantage of the concentrator is the disturbing force due to the solar pressure that acts on the large mirror surface. For example, a 100 m diameter concentrator implies 0.07 N of thrust at 1 AU when directly pointing towards the sun. To partly counteract that force we suggest aligning it with the gravitational force of the NEO. But, a much larger portion of pressure might result from the up-streaming vapor. This vapor stream poses a key problem during operation, too. The pollution of the collector surface due to the evaporated NEO material (vapor and debris) would result in a degeneration of the optical components [4]. This implies a threat to the mirror when partly exposed to the vapor jet. Particles moving at high speed could penetrate the mirror foil while slower particles could deposit on the mirror surface. This would be in addition to the vapor deposition on the reflecting surface. These procedures would negatively impair the efficiency of the mitigation (comparable to the degradation of solar cells on a spacecraft). Most probably the vapor plume expands towards a hemispherical vapor cloud, whose dust concentration depends on the distance and direction from the spot.

Concentrator Protection Devices: To avoid too many losses the mirror should be positioned outside of the main evaporation plume whose main elongation is assumed to be normal to the surface tangent. Therefore, Melosh et al. proposed a free-flying secondary mirror that redirects the focused beam and allows locating the primary mirror far away from the evaporating site. The secondary mirror would be much smaller than the primary mirror and could be exchanged if polluted. The use of secondary and tertiary mirrors to protect the primary one does not necessarily improve the situation since then the problem is handed over to those mirrors. The extent of degradation of reflectivity is not well known by now. Further analysis and simulations are needed to gain data close to reality. Nevertheless, it has to be guaranteed that the mirror foil will not disrupt if hit by debris. This could be achieved through a honeycomb cell structure of the foil where the propagation of fissures stops at the boundary of the cell. If these cells are small enough, the damage by penetration could be minimized. Besides, some simple and therefore low-cost options to avoid or slow down degradation are: (1) The use of double-sided primary and secondary mirrors for simply switching to a new second mirror surface, which doubles the operating time. (2) The use of several transparent foils to cover the mirrors, which will be stripped off when polluted. This approach extends the operating time depending on the number of removable foils, but each foil reduces the efficiency of reflectivity by a small factor. (3) The use of a movable transparent protecting foil, which covers the mirror surface like a blind. If the active area is polluted the foil will be rolled to one side while a fresh foil is pulled out of a protecting drum on the other side. The efficiency of reflectivity is only reduced by one foil. The operating time increases according to the amount of protecting foils available.

These mechanical protection concepts will increase the overall system mass slightly, but they might be essential for a successful operation. Further, the use of secondary mirrors allows for optimal thrust vector orientation. Several secondary mirrors on the same orbit around the NEO would enable a quasi-constant operation. Another important aspect could be the use of non-imaging mirrors as proposed in [4].

Systems Performance Simulation: In Voelker [6] design proposals and mass models for various solar concentrators have been derived. To give an example of the concentrator capabilities, a small system has been chosen that would fit into the limited payload

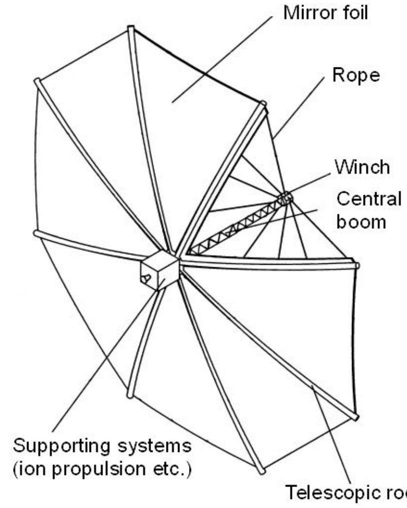

Fig. 2: System design of parabolic solar concentrator [6].

capacity of current available launchers. Here, we consider a 100 m diameter facet concentrator system (figure 2), which would weigh about 2000 kg (spacecraft and concentrator). At a 1 AU solar distance such a concentrator would produce a 10 m spot onto the NEO surface, which is equivalent to 220 N of force when applied to a silicate material. From the NEA database, which is maintained at the European Asteroid Research Node (E.A.R.N) by Gerhard Hahn [7], one PHA has been selected for demonstration: 2000 WC1. Assuming that this object belongs to the C-type group (albedo of 0.04), its diameter is approximately 210 m (H = 22.5). Further, the density is assumed to be 3 g/cm³. Figure 3 is a plot of the orbital evolution of this object. Here, the unperturbed orbit has been computed until the year 2010. Then, the deflection (220 N parallel to orbit velocity) has been applied for the duration of 400 days followed by a 10 years coasting phase. The orbital evolution has been compared to the unperturbed orbit. Here, the orbital displacement means the distance between diverted and unperturbed NEO positions at given epochs. As a result of the interaction, the semi-major axis is slightly enlarged causing a delay of the perturbed object along its orbit path with respect to its unperturbed position. As a consequence the displacement of the NEO from its unperturbed orbit increases constantly with time. This confirms the importance of an early discovery and interaction. The variations in the plot are due to perihelia (ups) and aphelia passes (downs). After 10 years of coasting phase the miss distance would be about 100 Earth radii.

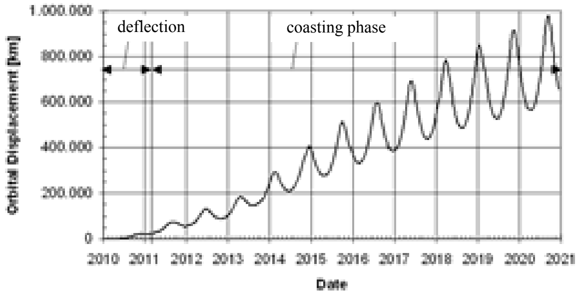

Fig. 3: Simulation of orbital displacement of 2000 WC1 (C) after solar concentrator interaction.

Solar Concentrators for in-situ experiments: For technology demonstration a small space-probe could be built at low costs within short time. A deployable 4 m diameter concentrator would probably weigh less than 4 kg and could be easily attached to a small spacecraft such as the proposed NEOX. When equipped with instruments, e.g. a mass spectrometer, material properties of the target NEO could be studied, too. At a 1 AU sun distance, such a small concentrator would excavate a 1 m deep hole when applied to a comet, or a 20 to 30 cm deep hole for a stony asteroid respectively. Thus, one could prove and demonstrate the deflection capabilities of solar concentrators along with the conduction of scientific experiments. Before, extensive ground experiments under vacuum conditions should be conducted to examine dedicated thermal properties of meteoritic materials and to understand the process of vaporization (e.g. shape of vapor plume, vapor deposition process, etc.).

Magnetospheric Plasma Propulsion: The idea of magnetospheric plasma propulsion is related to the solar sail concept concerning that both tap the ambient solar energy to provide thrust to a spacecraft. But, solar sails suffer from their mechanical structure – if large spacecraft or even small asteroids have to be propelled, physical limits will be reached, e.g. the system mass and problems accompanied by deploying that large structures. Thus, Winglee et al. [8] invented a revolutionary propulsion concept for interplanetary space missions, the Mini-Magnetospheric Plasma Propulsion (M2P2). Here, an electromagnetic coil generates a magnetic field that thereupon is enlarged due to the injection of plasma. This magnetic bubble will intercept the solar wind, which at a distance of 1 AU has a particle density of about 6 cm^{-3} and moves at speeds of 300 to 800 km/s. This results in a constant dynamic pressure of 2 nPa. If the magnetic field cross section is large enough a continuous force (few to tens of N) could be provided. We propose to use such a system for NEO diversion. Although the generated thrust is low, this system could be operated for a long duration (several months) to divert a PHO. One significant problem is the attachment of this propulsion system to the NEO. Anchoring might work when dealing with a slow rotator. Another weak point might be the force alignment. When operating with small thrust over long periods the force should be aligned with the NEO's velocity vector. But, for the mini-magnetospheric plasma propulsion, the largest portion of the generated force will point in radial direction (sun-NEO direction). To increase the performance, the magnetic axis could be tilted 45° into the solar wind, which would result in a larger magnetosphere (because the magnetic field is stronger at the poles) and an azimuthal force component (lift) [8].

Systems Performance Estimation: A hypothetical system has been scaled based on the system characteristics given in [8]. Here, we assume a 60 km artificial magnetosphere. To maintain the electromagnetic field and to generate the plasma one would require about 7 kW of power, which could be provided by a radioactive isotope power system weighing about 1.2 tons. Together with the equipment (electromagnetic coil and

RF antenna) and the "fuel" for a one year operation one would probably end up with a 3 ton spacecraft. Assuming an efficient coupling to the asteroid from the previous example a force of 90 N radial and 11 N azimuthal could be delivered. The corresponding orbital evolution is plotted in figure 4. Note that 2000 WC1 is now considered as an S-type object (albedo of 0.20). Thus, its size decreases from 210 m to only 90 m. This explains why a similar performance is achieved with a much smaller force (actual tangential component 11 N vs. 220 N in example for the solar concentrator).

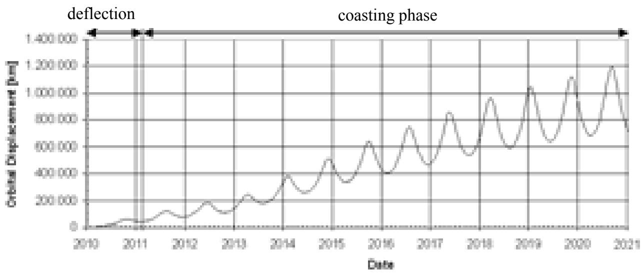

Fig. 4: Simulation of orbital displacement of 2000 WC1 (S) after interaction with magnetospheric plasma propulsion.

Magnetospheric Plasma Propulsion for NEO Exploration: According to Winglee et al. the M2P2 could become revolutionary propulsion for interplanetary travel. Small spacecraft of 100 kg or 200 kg mass could be accelerated to speeds of 75 km/s or 50 km/s respectively. This would enable us to conduct exploration missions to asteroids and comets in a much faster way. Objects could be explored that are not accessible with current propulsion systems and the additional help of gravity assists. Even if a coupling to NEO's for deflection purposes was not feasible, this propulsion system would be of great importance for reaching the hazardous object to apply a suitable technique. For example, kinetic energy impacts would highly profit from the enormous relative speed available by the M2P2.

Summary: In this work two future mitigation technologies have been proposed and investigated: the solar concentrator and the magnetospheric plasma propulsion. A small solar concentrator (4 m diameter, deployable) could be attached to a small spacecraft to conduct physical characterization at a NEO and to demonstrate its deflection capabilities at same time. If successfully developed and tested, the mini-magnetospheric plasma propulsion could be of importance for both reconnaissance and mitigation. An overview of both systems, relevant physical parameters for the interaction, a brief conceptual analysis, and examples for orbit diversion have been presented.

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HOW WELL DO WE UNDERSTAND THE COMETARY HAZARD?. Matthew Knight, Michael A'Hearn, *Department of Astronomy, University of Maryland, College Park MD 20742, USA, (mmk8a@astro.umd.edu, ma@astro.umd.edu).*

1. INTRODUCTION

A common concern of the general public today, one which receives much attention in the press, is the peril of an asteroid or comet colliding with the Earth. In recent years, block-buster movies such as Armageddon and Deep Impact have raised public awareness of the issue. While the general public can be assured that astronomers are actively searching for such potentially hazardous objects, how well is this being accomplished?

Over the last few years, a number of surveys have been implemented to search for Near Earth Objects (NEOs). These surveys are optimized to find Near Earth Asteroids (NEAs), small objects on nearly circular orbits with short periods. These surveys have been very successful at finding NEAs, with discovery rates of hundreds per year, and it is believed that most large NEAs have been or will soon be found. Combining this large detection rate with statistics on the rates of impacts gleaned by counting craters on the Earth, the Moon, and other solar system bodies makes the impact hazard from asteroids reasonably well understood.

In contrast, the impact hazard posed by comets is still quite uncertain. Due to their large rates of motion across the sky, differing locations on the sky, and extended, diffuse appearance, comets are difficult for traditional NEO surveys to detect. The long periods of many comets make it impossible to approach mitigation of the cometary hazard in the same way as for NEAs and Jupiter family comets. Additionally, the size and composition of typical cometary nuclei are not well understood. These factors combine to make it difficult to estimate the fraction of the NEO hazard due to comets. In hopes of better understanding the cometary hazard, and thus the NEO hazard as a whole, this work examines the comets discovered by survey and by non-survey astronomers since 1 January 1999.

A preliminary study of comets discovered from 1990 to 1998 found that there were 31 non-survey discovered comets (comets discovered by amateurs or by professional astronomers not part of a search for NEOs) with perihelion distance $q <$ 2 AU, of which 25 were discovered by amateurs. Of the 25 amateur discoveries, 11 had $q < 1$ AU. Additionally, 6 of the 31 non-survey discoveries (2 of 25 amateur discoveries, 4 of 6 professional discoveries) should have been in the field of view of at least one of the following surveys prior to discovery: the Palomar Digital Sky Survey (DPOSS), the Second Palomar Observatory Sky Survey(POSS ii), or the Second Epoch Southern Red Survey (AAOR), however the matching frames have not been re-searched to find the comets. The relatively large number of potentially hazardous comets discovered by amateurs from 1990–1998 encouraged us to undertake a more thorough study of the properties of survey and non-survey discovered comets.

This work presents a study of the comets discovered since 1 January 1999, the date being chosen to mark the point at which most of the NEO surveys were operating at relatively high efficiency. The sungrazing comets discovered by SOHO/LASCO during this time were disregarded, as they were all too small to have been visible from the Earth when they were far enough from the Sun to be detectable by surveys, nor did any survive perihelion passage during this time. However, the two comets discovered by the SWAN instrument on SOHO were included. Additionally, three comets (P/2000 ET_{90} P/Kowal-Mrkos, P/2000 S2 P/Shoemaker-LINEAR, and P/2000 SO_{253} P/Anderson-LINEAR) were removed because they were all reapparitions of previously observed comets, and therefore not new discoveries. After removing the SOHO/LASCO comets and the previously observed comets, a sample of 136 newly discovered comets remained.

Survey	Discoveries	Co-Discoveries
LINEAR	64	6 (4 NEAT, 1 LONEOS, 1 Spacewatch)
NEAT	18	4 (LINEAR)
LONEOS	17	2 (LINEAR, Catalina)
Spacewatch	5	1 (LINEAR)
Catalina	4	1 (LONEOS)
BATTERS	1	0
Total	109	7

Table 1: Statistics of survey discovered comets since 1 January 1999

The sample of 136 comets was then divided into two groups: those discovered by surveys intentionally searching for comets and other NEOs, and those not discovered by such surveys. The survey sample contained 116 comets, including discoveries by LINEAR (Lincoln Near Earth Asteroid Research), NEAT (Near Earth Asteroid Tracking), LONEOS (Lowell Observatory Near Earth Object Survey), Spacewatch, Catalina Sky Survey, and BATTERS (Bisei Asteroid Tracking Telescope for Rapid Survey). A breakdown of discoveries by each survey can be seen in Table 1. The remaining 20 comets were found by amateurs or by professional astronomers not part of NEO surveys.

The samples of survey and non-survey discovered comets were compared to better understand the selection effects which cause the surveys to miss some comets. The effects of perihelion distance, q, on discovery are discussed in §2, the effects of peak brightness on discovery are discussed in §3, the effects of inclination, i, on discovery are discussed in §4, and the effects of position on the sky prior to discovery are discussed in §5.

2. PERIHELION DISTANCE, q

An obvious selection effect is that it is easier to discover comets which are closer to the Sun, since comets are brightest at small heliocentric distances. Additionally, since brightness decreases as the square of the distance, comets which pass close to Earth near perihelion will appear brighter than comets

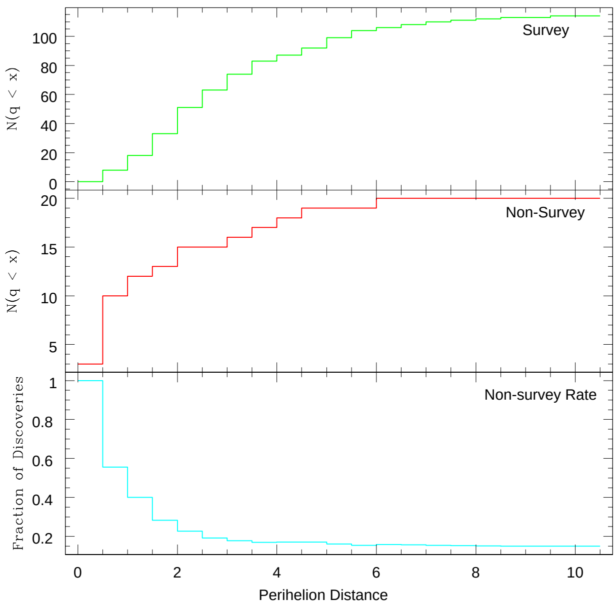

Figure 1: Cumulative number of comets discovered since 1 January 1999 with perihelion distance less than a given distance. *Top panel*: Survey discovered comets. *Middle panel*: Non-survey discovered comets. *Bottom panel*: Ratio of non-survey discoveries to the total number of discoveries (survey plus non-survey) interior to a given perihelion distance.

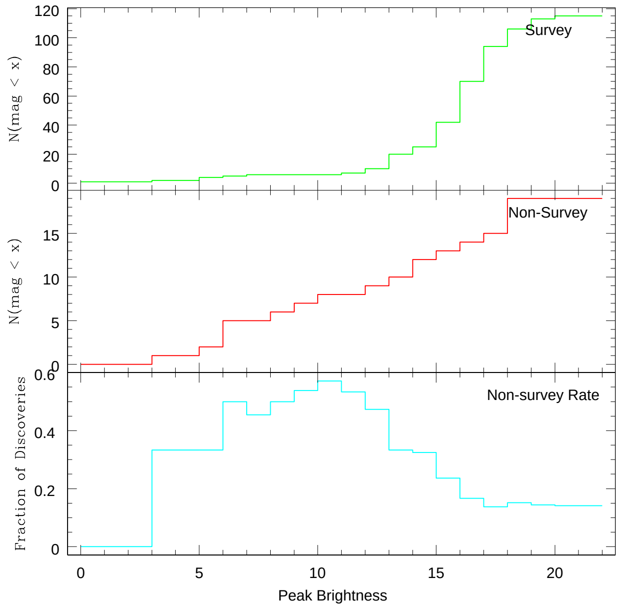

Figure 2: Cumulative number of comets discovered since 1 January 1999 brighter than a given magnitude. *Top panel*: Survey discovered comets. *Middle panel*: Non-survey discovered comets. *Bottom panel*: Ratio of non-survey discoveries to the total number of discoveries (survey plus non-survey) brighter than a given magnitude.

which pass farther away. These factors combine to make it easiest to to detect comets with small perihelion distances, however other factors can counteract this. Among these are their large rates of motion across the sky, differing locations on the sky, and extreme variation in brightness throughout their orbits. To analyze the dependence on perihelion distance, the cumulative number of comets discovered with perihelion distance less than a given distance is plotted in Figure 1.

In Figure 1, the top panel shows the cumulative number of discoveries by surveys while the middle panel shows the cumulative number discovered by non-surveys. The bottom panel gives the most revealing look at the relative distributions of q in the survey and non-survey samples. This plot shows the ratio of non-survey discoveries to the total number of discoveries (survey plus non-survey) interior to a given perihelion distance. The bottom panels reveals that all of the comets with $q < 0.5$ AU and nearly 60% with $q < 1$ AU were found by non-surveys. Few comets were found with large perihelion distance, thus the ratio in the bottom panel remains nearly flat beyond $q > 4$ AU.

Thus, the bottom panel of Figure 1 graphically demonstrates that non-survey observers are much better than the NEO surveys at detecting comets which pass close to the Sun. Half (10 of 20) of the non-survey detections had $q < 1$ AU, while only 8 of 116 survey detections had $q < 1$ AU. Beyond 3 AU, only 5 comets were discovered by non-surveys, whereas 53 were discovered by surveys, and 10 of the 11 discoveries with $q > 4$ AU were made by the surveys.

3. PEAK BRIGHTNESS

Similar to the selection effects favoring the discovery of comets with small perihelion distances is the preference for the discovery of brighter comets. Comets which have intrinsically brighter peaks are more likely to be detected for two reason. Most obviously, it is easier to detect brighter objects. Additionally, intrinsically bright comets are generally brighter than a given threshold for a longer period of time. Thus, for magnitude limited observations, bright comets will remain above the brightness threshold longer, increasing the chance of their discovery.

Using JPL's Horizon's Ephemeris generator, ephemerides were computed for 134 of the 136 comets discovered since 1 January 1999 (C/2000 S5 and C/2000 X3 were not in the database), and the peak brightness was determined for each. The cumulative number of comets discovered with peak brightness brighter than a given magnitude is plotted in Figure 2. As in Figure 1, the top panel shows the cumulative number of discoveries by surveys, the middle panel shows the cumulative number of discoveries by non-surveys, and the bottom panel shows the ratio of non-survey discoveries to the total number of discoveries (survey plus non-survey) which peak brighter than a given magnitude.

Comparison of the top two panels in Figure 2 reveals that the non-survey detections were roughly constant across the magnitude range, while the survey detections were weighted

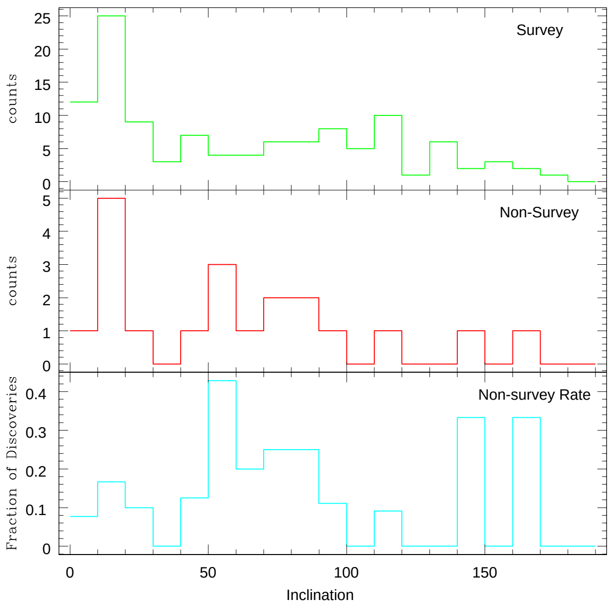

Figure 3: Histogram of inclination of comets discovered since 1 January 1999. *Top panel*: Survey discovered comets. *Middle panel*: Non-survey discovered comets. *Bottom panel*: Ratio of non-survey discoveries to the total number of discoveries (survey plus non-survey) in each histogram bin.

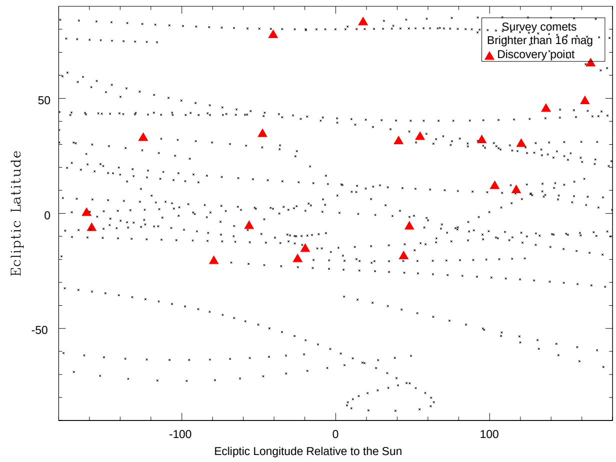

Figure 4: Position on the sky for 12 months prior to discovery for survey discovered comets brighter than 16^{th} magnitude. The red triangles represent the discovery date. Points are spaced every 5 days.

toward the faint end. That is, the non-survey discoveries included roughly equal numbers of bright and faint comets, while the surveys detected more faint comets than bright comets. This analysis is reinforced by the bottom panel of Figure 2, which indicates that non-survey discoveries represent ∼50% of the total number of discoveries brighter than 13^{th} magnitude, while representing only ∼20% of the discoveries brighter than 20^{th} magnitude. Alternatively, there were 90 survey discovered comets with peak magnitude fainter than 15^{th} magnitude, while only 7 non-survey discovered comets with peak magnitude fainter than 15^{th} magnitude. Thus, it appears that non-survey observers are much better than NEO surveys at detecting intrinsically bright comets.

4. INCLINATION, *i*

The effect of inclination on the detection of comets by NEO surveys or by non-survey observers is not as obvious as the effects of perihelion distance and magnitude. Slightly different than Figures 1 and 2, Figure 3 shows a histogram of survey discoveries in the top panel, a histogram of non-survey discoveries in the middle panel, and the ratio of non-survey discoveries to the total number of discoveries (survey plus non-survey) in each histogram bin in the bottom panel.

Looking at the top two panels in Figure 3, both the survey and non-survey discoveries were relatively constant for all inclinations, however there were slightly more discoveries having $i < 30°$ and slightly fewer discoveries having $i > 120°$. The bottom panel of Figure 3 indicates that there were relatively more non-survey discoveries at high inclination (50° – 90°) than at other inclinations. This apparent increase in detections at high inclinations may indicate a preference for non-survey observers to discover comets at high inclinations, however, if high inclinations were favorable for the detection of comets by non-survey observers, a similar peak in the ratio of discoveries for 90° – 130° (highly inclined, retrograde orbits) would be expected. The small number of observations may be responsible for this discrepancy, or there may be selection effects influencing the discovery of highly inclined retrograde comets such as morning/evening discoveries or predominantly northern/southern hemisphere visibility, however they are beyond the scope of the current work. In any case, we conclude that there are no strong inclination preferences in the discovery of comets by either survey or non-survey observers.

5. POSITION ON THE SKY

The segment of each comet's orbit for up to 12 months prior to discovery during which it was brighter than 16^{th} magnitude is shown in Figures 4 (survey discovered) and 5 (non-survey discovered). The positions are plotted relative to the Sun in 5 day intervals, and the large red triangles represent the discovery date.

The positions on the sky at the time of discovery are spaced throughout the latitude-longitude plane in both figures, however there are more survey discoveries above 0° latitude, and more non-survey discoveries below 0° latitude. These distributions are likely due to the geographic location of the observers. Most NEO surveys are located in the northern hemisphere, thus scanning the northern sky much more thoroughly than the southern sky, and being unable to scan some parts of the southern sky at all. As a result, more comets are missed by the surveys in the southern sky, making it more likely that they will be discovered by non-survey observers.

6. CONCLUSION

Despite the increased number of comet detections over the

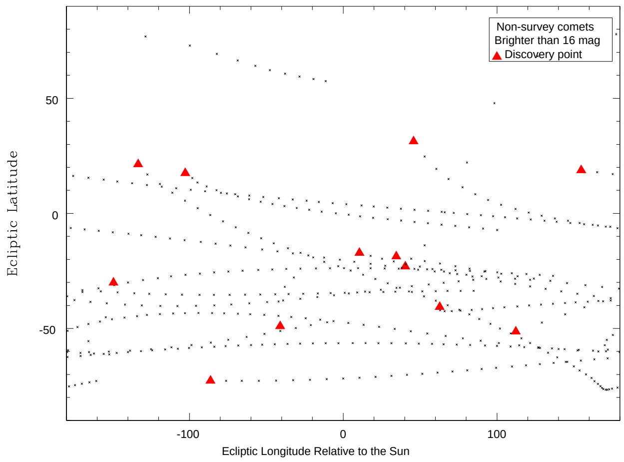

Figure 5: Position on the sky for 12 months prior to discovery for non-survey discovered comets brighter than 16^{th} magnitude. The red triangles represent the discovery date. Points are spaced every 5 days.

last 4 years due to the proliferation of NEO surveys, amateur astronomers continue to find a significant number of comets with small perihelion distances. During the period 1990 – 1998, 25 comets with $q < 2$ AU were discovered by amateur astronomers, an average of 2.77 per year. From January 1999 until August 2002, 10 comets with $q < 2$ AU were discovered by amateur astronomers, an average of 2.73 per year. While the statistics are small, this indicates that the discovery rates of amateur astronomers are unaffected by the NEO surveys, and thus the surveys are not finding many of the potentially hazardous comets.

Comparison of the 136 comets discovered since 1 January 1999 reveals that non-survey observers are much better than the surveys designed to search for NEOs at finding bright comets with small perihelion distances ($q < 2$ AU). Since large comets are generally brighter, and in order for a comet to collide with the Earth it must have $q < 1$ AU, the comets which the surveys are missing are precisely the ones that most need to be detected.

Since the beginning of 1999, 10 of the 18 newly discovered comets which reach perihelion interior to the Earth's orbit were not found by the NEO surveys, but rather by non-survey observers. This large fraction of missed comets by the surveys indicates that the hazards of impacts by comets are still very uncertain due to selection effects of the surveys. These selection effects cause NEO surveys to miss bright comets with small perihelion distance. There does not appear to be a strong preference for any particular inclination, however more comets are missed in the southern sky than the northern, underscoring the need for dedicated near Earth comet surveys in the southern hemisphere.

These and other selection effects must be accounted for in order to better understand the cometary hazard and to improve our current ability to detect potentially hazardous comets. Due to their diffuse appearance, large rates of motion across the sky, varying locations on the sky, and extreme variation in brightness throughout their orbits, comets are not being detected effeciently using the current asteroid detection techniques. Therefore, surveys to protect us from potentially hazardous comets must be conducted very differently from surveys for asteroids, both because the long periods of these comets make cataloging them long in advance of a threat impossible and because the surveys are not finding them.

Characterizing The Comet Impact Hazard : Results From an Ongoing IR Survey of Cometary Dust and Nuclei

C.M. Lisse[1], M.F. A'Hearn[1], Y.R. Fernandez[2]

[1]University of Maryland, Department of Astronomy, College Park, MD 20742

[2]Institute for Astronomy, University of Hawaii, 2680 Woodlawn Drive, Honolulu, HI 96822

Introduction: The population of comets represents a small, but finite and largely uncharacterized, impact hazard to the Earth. In this abstract we present the results relevant to impact hazard mitigation from our survey of the nuclear surface properties and emitted dust of the brightest near-Earth comets over the last 11 years .

The largest threat of Earth impacts in terms of highest probability comes from the short period (SP) comets; the highest potential for a major impact with little advanced notice comes from the Oort cloud long [period (LP) and dynamically new (New) comets [1]. Little can be done to chart the latter hazard, other than maintain a number of sensitive all-sky searches for incoming objects. The SP comets, however, are a much more tractable problem. In the following, we will tend to emphasize our studies of SP comets.

The present population of ~200 short period (SP) comets [2], daughters of the Kuiper-Edgeworth planetisimals found outside Neptune's orbit, have been shown to be the known component of a population of approximately 500 to 1000 total comets with radius ≥ 300 m [3]. Further, as we will show below, the SP comets evolve due to the effects of solar insolation until they become devolatilized and dormant C or D-type "asteroids". The SP comet population thus has ties to both the K-E and asteroidal populations. The SP population is dynamically unstable in its present day configuration to ejection from the inner solar system on timescales of $\sim 10^5$ years [3]. Therefore the current population of SP comets is a relatively recent sampling of the K-E belt. Study of the links between these populations by large statistical surveys over many different SP ages will yield the evolutionary path taken by the K-E planetisimals in the present day solar system, and thus help determine the nature of the impact hazard presented by a given type of SP comet.

Measurement of a comet's mid-IR thermal emi s-sion, combined with simultaneous measurements of scattered optical/near-IR sunlight from the nucleus and coma dust, is the most unambiguous approach to measuring the comet's nuclear size and surface properties (via the emitted surface dust). Both scattering and emission measurements of the nuclear surface are usually difficult because the brightness of the coma, which scales inversely with geocentric distance, usually completely overwhelms the brightness of the nucleus, which scales as the inverse square of geocentric distance. However, the availability of modern, highly sensitive, linear, diffraction-limited IR cameras now makes a search for residual thermal continuum emission from cometary nuclei possible after removal of the coma emission [4].

In this work, simultaneous optical and thermal i n-frared imaging photometric observations at multiple wavelengths were analyzed using dynamical and spectral models of the coma [5] to update the dust emission rate estimates of Kresak and Kresakova [6] and the nucleus size estimates of Jewitt [7]. A discussion of the details of the photometric analysis is beyond the scope of this work; see [8] for more detail. From the resulting nuclear sizes and dust emission spectra and rates, we are able to derive estimates for the nucleus size versus rotation period, of a large population of dormant/extinct SP comets, and of the nature of the cometary surface environment for the 16 survey comets observed in the last 11 years.

Distribution of nuclear sizes and rotation periods. The observed distribution of cometary sizes and rotation periods is shown in Figure 1. For comparison, the critical rotational breakup limits for spherical cometary bodies from [9] is also shown. The most striking result is that the cometary nuclei, including all the SP comets, cluster inside the region allowed by rotational stability of highly fractured porous icy material, suggesting both the strong role of rotational stability in the evolution of comets. Only the very large comets Hale-Bopp (in the damaged region) and Chiron (in the forbidden region) lie outside the allowed region. This finding seems consistent with the extremely high emission activity of Hale-Bopp - due to multiple large active areas created by deep subsurface fissures [9]; and the different internal mechanical structure of the pre-SP comet (i.e., Centaur) Chiron – having never been inside the ice line at ~ 3 AU, no thermal wave has propagated downward to substantially alter the water ice structures in the comet's interior. It suggests that these bodies will undergo a large amount of change in the future, splitting to form a number of smaller, rotationally stable bodies. It is also interesting to note that the highly publicized disruption of comet C/1999 S4 (LINEAR) in the summer of 2000 could not have been driven by rotational instability – as before breakup the comet falls clearly in the allowed region. This strongly suggests the disruption was due to some process other than rotational fissioning, such as runaway volatilization [12]. Compared to the main-belt and NEA asteroid populations, comets are small, very slow rotators.

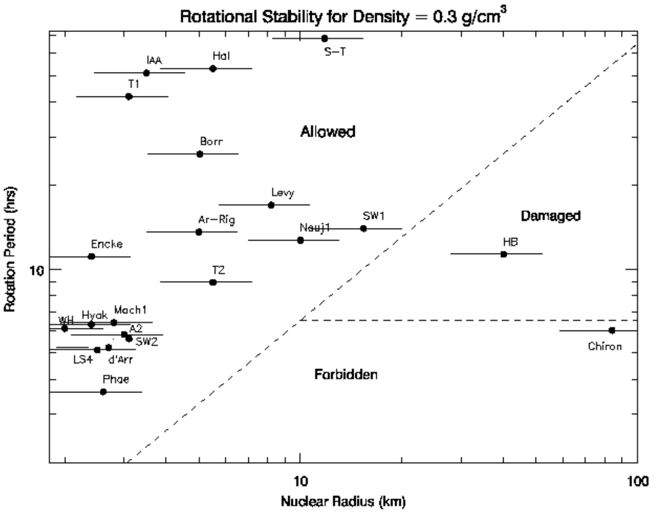

Figure 1 – Survey comet rotation period versus effective nuclear radius. The observed rotational periods and radii are represented by filled circles. The solid lines denote the critical rotational breakup limits for spherical cometary bodies from [9]. The limits have been calculated using the rotational stability model of Davidsson [10], assuming a bulk density of 300 kg m^{-3} and material strength according to Greenberg *et al.* [11].

In terms of the potential impact hazard, this result suggests the most likely impact hazard will come from an SP comet a few km in size, rotating with period greater than ~5 hours.

Undetected dormant comets. By comparing our estimates of the expected lifetime versus dust loss to dynamical models of the orbital evolution of the short period comets [8], we find that the short period comets do not become extinct by long term dust and gas loss (Figure 2) ; rather, they mainly turn-off due to thick mantle formation within 10^3 – 10^4 years and become indistinguishable from "primitive"-type asteroids. A smaller fraction destructively disintegrate, dynamically evolve out of the solar system, impact the Sun, or fragment into unobservedly small meteoroids. The expected current total number of inner solar system SP comets, including inactive comets, is a factor of 3 to 6 higher than the observed number [3]. Observational proof for the existence of dormant/extinct comets masquerading as C/D type asteroids is beginning to come from the results of new surveys of small near-earth asteroids (NEA's) and main-belt asteroids (MBA's), which have produced, out of an extremely limited sampling of (sky location, object intrinsic magnitude) phase space [13], a number of unusual objects (> 20) with very low geometric albedos, little or no outgassing activity, and orbits akin to the short period and Halley-class comets. It thus appears that at least a few of the SP comets become "dormant" and lose all their outgassing activity before being scattered out of the inner solar system (Lisse 2001) [8].

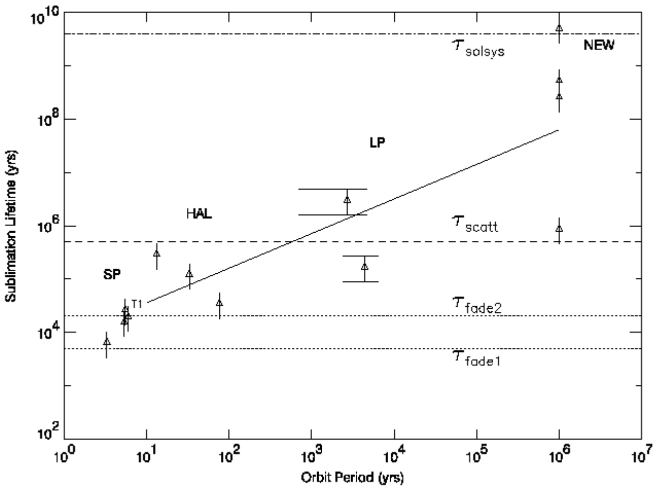

Figure 2 - Time Until Turnoff of Activity. The total lifetime versus sublimation is derived using knowledge of the comet's orbit, initial mass, and Q_{dust} at time t=0. The derived lifetimes correspond to 10^3 to 10^5 orbits. The mean dynamical lifetime estimated by Levison and Duncan (1994) SP comets is denoted by the dashed line, and the range of their derived "fading times" are denoted by the dotted lines. Note that the IR survey results demonstrate that the SP comets are robust to sublimation longer than the fading time range, implying the existence of extinct comets in the solar system.

In terms of the potential impact hazard, we can expect as many as 1000 SP comets of > 0.5 km radius, with very low geometric albedo (2-4%), currently inside 5 AU, with the majority of these bodies yet to be discovered.

The nature of the cometary hazard's surface. The nature of the cometary surface must be accounted for when any attempts at remediation of a comet impact hazard is considered. In the absence of direct measurements by in situ probes, the best understanding we have of the nuclear surface is by studying the material emitted from the surface into the comet's extended, gravitationally unbound atmosphere (i.e., the coma). Our photometric observations of cometary nuclei naturally provide us with measurements of the coma dust as well.

With the 16 comets currently in our database, we are finding strong trends in the aggregate dataset of dust particle size distribution (PSD), total emission rate, and emission rate vs. time versus dynamical class (Figure 3). The majority of the observed SP comets emit large, dark dust particles of high mass, while the LP comets emit most of their dust surface area (but not mass) in small, high albedo particles. The only two SP comets to show evidence for small particle emission [14] are both classed by Whipple [15] as "young" or new SP comets. The New comets, which can be considered to be very young LP comets, appear to act like the SP comets. A check of some 40 literature comet observations in the thermal IR has verified these trends to a probability of error less than 1 x 10^{-4}.

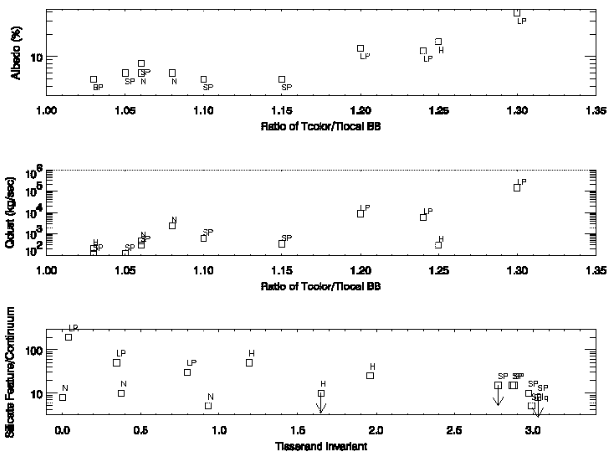

Figure 3 - Correlations in the observations of emitted cometary dust by albedo, silicate feature amplitude/continuum ratio, dust color temperature, Q_{dust}, and Tisserand invariant of the parent comet. (a) Comparison of the dust temperature and albedo (not shown is a correlation of the dust albedo and silicate feature strength, which demonstrates a similarly strong correlation); **(b)** of the dust production rate and the temperature of the dust; and **(c)** of the strength of the silicate feature and the Tisserand. There are clear trends and distinct groups by dynamical class – the LP comets produce the most dust with the hottest color temperature, highest albedo, and largest silicate feature. The New and SP comets produce little dust and what they do produce is cold, low albedo, and without much silicate feature. The Halley comets are between the two extremes.

From these trends we have inferred [8] that the different behaviors by class are due to the combined effects of cometary evolution on the structure of the cometary surface and the depletion of cometary volatiles. The majority of SP comets are highly evolved and relatively devolatilized, with mature mantles. The New comets have a thin "primordial" mantle grown from cosmic rays, solar UV, etc. over the age of the Solar System, which survives until they suffer a few perihelion passages; we know they are rich in volatiles from their later LP behavior. The LP comets are mostly rich in volatiles with active, fresh surfaces, probably the most "pristine" and fresh surface of any of the cometary types. The Halley family comets, with much shorter orbital periods but rapid removal rates, can be either little or highly evolved, leading to no clear evolutionary trends.

In terms of the impact hazard to Earth, based on these results, we expect the surface of a New or LP comet to be volatile rich, with a thin processed mantle on the newer Oort cloud comets; and the surfaces of all but the youngest SP to consist of a thick devolatilized but porous and fractal refractory surface.

Future Work. The results of this work are based on a total of 16 comets, with 4 in each dynamical class [8]. While we have been able to check the dust results versus ~40 other measurements in the literature, no such database exists for the nuclear size and rotation rates. Thus increasing the number of observed comets can greatly improve the robustness of the conclusions derived for the mechanical (size, rotation period, bulk modulus, density). Our work suggests that the best results on the size of cometary hazards are best determined with the body relatively inactive beyond the ice line [16], which unfortunately puts the body at > 2 AU from the Earth. Thus in order to perform a consistent, complete survey of the most dangerous and best known SP cometary nuclei hazards, the latest IR and optical imaging technology will be required – such as the 8 to 10 m class ground based telescopes and HST/SIRTF. We also note that the largest number of the potential SP comet hazards have yet to be identified; while on the order of 1 km in size, they will be of extremely low albedo versus the majority of NEA's and thus potentially undetectable in the current Spaceguard surveys. Searches for all objects down to 100 m effective radius between 1 and 5 AU distance from the Sun should detect the bulk of these objects.

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Deflecting Impactors at 90°

Claudio Maccone

Member of the International Academy of Astronautics
Address: Via Martorelli 43, I-10155 Torino (TO), Italy
E-mail: clmaccon@libero.it

ABSTRACT. In a recent paper (Acta Astronautica, Vol. 50, No. 3, pp. 185-199, 2002, listed are ref. [1]) this author gave a mathematical proof that any impactor (= asteroid or comet) could be hit at an angle of 90° if hit by a missile shot not from the Earth, but rather from the Lagrangian Points L3 or L1 of the Earth-Moon system.
Based on that mathematical theorem, in this paper the author shows that:

1) This defense system would be ideal to deflect small impactors, less than one kilometer in diameter. And small impactors are just the most difficult ones to be detected enough in advance and to a sufficient orbital accuracy to prove that they are impactors indeed.
2) The deflection is achieved by pure momentum transfer. No nuclear weapons in space would be needed. This is because the missiles are hitting the impactor at the optimum angle of 90°. A big steel-basket on the missile head would help.
3) In case one missile was not enough to deflect the impactor off its Earth-collision hyperbolic trajectory, it is a wonderful mathematical property of confocal conics that the new slightly-deflected impactor’s hyperbola can certainly be hit at 90° by another and slightly more eccentric ellipse! So, a sufficient number of missiles could be launched in a sequence from the Earth-Moon Lagrangian points L3 and L1 with the absolute certainty that the SUM of all these small and repeated deflections will finally throw the impactor off its collision hyperbola with the Earth.

1. Short Review About The Five Earth-Moon Lagrangian Points

Let us start by reviewing what the five Lagrangian points of the Earth-Moon system are and where they are located, even if this is well-known material to astrophysicists and space scientists alike. In 1772 Joseph Louis Lagrange demostrated that there are five positions of equilibrium in a rotating two-body gravity field: three are situated on the line joining the two massive bodies, and are nowdays called “colinear points”, or L1, L2 and L3, as shown in Figure 1 for the Earth-Moon system. The other two (called L4 and L5) form equilateral triangles with the two massive bodies, and so are called “triangular points”.

The locations of the three colinear points L1, L2 and L3 are found as the real roots of an algebraic equation of the fifth degree, originally due to Lagrange, that can only be solved by resorting to Taylor series expansions. Fortunately, the relevant three different Taylor expansions converge rapidly, so one may take into account just three terms in each Taylor expansion to get approximations that are quite satisfactory numerically. Here we just state that, assuming for the Earth-Moon distance the numerical value of R = 384,401 km, then:

1) The distance between the Moon and the Lagrangian point L1 equals 0.1596003*R, that is 61350.317208 km. Consequently the Earth-to-L1 distance equals 0.8403997*R, that is 323050.482792 km.
2) The distance between the Moon and the Lagrangian point L2 equals 0.1595926*R, that is 61347,568938 km.
3) The distance between the Earth and the Lagrangian point L3 equals 0.992886*R, that is 381666.370650 km.

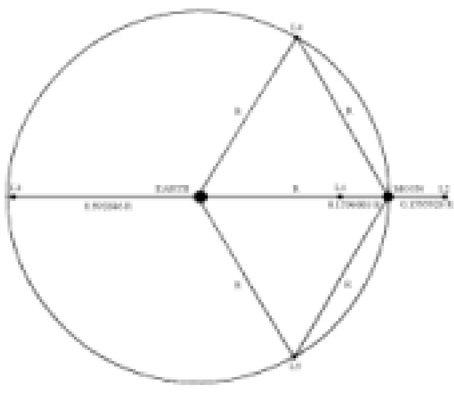

Figure 1.
The five Lagrangian points of the Earth-Moon system and their distances from Earth and Moon expressed in terms of R, the Earth-Moon distance (supposing the Moon orbit circular, in the first approximation).

2. Impactor-Confocal Trajectories for the Best Deflection of Impactors

This section is devoted to the mathematical theory of ***confocal conics*** as the ***best trajectories*** for deflecting impactors by virtue of missiles launched from either of the two colinear Lagrangian points L1 and L3. The triangular points L4 and L5 are excluded from this theory because the trajectories of missiles launched from them is not planar, and so much more complicated. Also, the Lagrangian points L1 and L2 of the Sun-Earth system are excluded from the following considerations, inasmuch as they would require the theory of perturbations. In conclusion, we just consider the ***Planetary Defense from the nearest two Lagrangian points, L1 and L3.***

Consider the equation of the ellipse $\frac{x^2}{a_{ell}^2} + \frac{y^2}{b_{ell}^2} = 1$ (2.1), where $a_{ell}^2 = b_{ell}^2 + c_{ell}^2$ (2.2) and $0 \le e_{ell} = \frac{c_{ell}}{a_{ell}} < 1$ (2.3) and the equation of the hyperbola $\frac{x^2}{a_{hyp}^2} - \frac{y^2}{b_{hyp}^2} = 1$ (2.4) where $c_{hyp}^2 = a_{hyp}^2 + b_{hyp}^2$ (2.5) and $e_{hyp} = \frac{c_{hyp}}{a_{hyp}} > 1$ (2.6). If the ellipse and the hyperbola have the same value for c, namely if $c_{ell} = c_{hyp} = c$ (2.7) then the ellipse and the hyperbola are said to be "confocal" (or "omofocal"), inasmuch as the two focal points located at ($-c$, 0) and (c, 0) are common to both. Because of (2.7), (2.3) and (2.6) the above confocality definition translates into the equation $a_{ell}\, e_{ell} = a_{hyp}\, e_{hyp}$ (2.8). Actually, by doing so, we have really defined two families of confocal conics. One is the family of ∞^1 confocal ellipses, and the other is the family of ∞^1 confocal hyperbolas. In fact, each one of the confocal ellipses has a different value of both a_{ell} and e_{ell}, but the latters' product always equals the constant value c (as from the confocality condition (2.8)) so that you either assign a_{ell} and determine e_{ell} by virtue of (2.8), or the other way round. The same for the hyperbolas. Figure 2 shows two confocal ellipses and two confocal hyperbolas (the "missing" vertical parts in the graphs are just because the computer does not know what infinity is !).

The great property of confocal conics is that the any pair of different confocal conics, namely one ellipse and one hyperbola, always intersect each other at angles of 90°. In other words, the family of ellipses (2.1) and the family of hyperbolas (2.4), when related by the confocality condition (2.8), form two families of ***orthogonal trajectories.*** This is a well-known result proven in any textbook of elementary analytical geometry. Not to leave the reader with doubts, however, we just hint the proof in a few lines! Call (x_0, y_0) the intersection point of the two conics (actually there are four such intersections for each pair of conics, but pretend you don't know about it!). Then, even high-school students know that the tangent line to the ellipse at point (x_0, y_0) has the equation

$\frac{x\,x_0}{a_{ell}^2} + \frac{y\,y_0}{b_{ell}^2} = 1$ (2.9) and the tangent line to the hyperbola at point (x_0, y_0) has the equation $\frac{x\,x_0}{a_{hyp}^2} - \frac{y\,y_0}{b_{hyp}^2} = 1$ (2.10). Solving the last two equations with respect to y, one finds the two angular coefficients of these tangent lines. Multiplying then these two angular coefficients, one gets, after some reductions, -1 as the result. This shows that the tangents to the ellipse and to the hyperbola are orthogonal to each other.

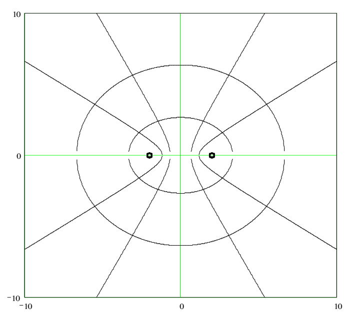

Figure 2.
The two families of ∞^1 confocal ellipses and ∞^1 confocal hyperbolas.

Is all this good for deflecting impactors ?

Yes - is our answer - and here follows the sequence of logical steps leading towards the application of confocal conics as the ***best*** trajectories for missiles shot from the Lagrangian points :

1) Consider only one of the two focuses (or "foci", in Latin), namely the one "on the left". Imagine the Earth is there. Then both the confocal ellipse and the confocal hyperbola are physical trajectories (paths) that moving bodies aroud the Earth follow naturally, because this is just Kepler's First Law. But, which body is following which path ?

2) A dangerous impactor arrives from infinity, namely from outside the sphere of influence of the Earth. So, it can only follow a ***hyperbolic*** trajectory with respect to the Earth, with the focus of this hyperbola located just at the center of the Earth (at least in the first approximantion, to which we confine ourselves here). Also, the incoming impactor is to be regarded as "dangerous" only if its path crosses the Earth, namely if the perigee of its hyperbolic trajectory is smaller than the Earth radius: $c_{hyp} < R_{Earth}$.
3) What is the counterpart of the ellipse confocal to the impactor's hyperbola ? Our answer is: the confocal ellipse is the physical trajectory of a missile launched against the incoming dangerous impactor from any point in space, but better from the two colinear Lagrangian points, L1 and L3, located each on one side of the Earth "for better defense". Points L4 and L5 could also be used, but the relevant missile's orbit calculations would be more involved as three-dimensional. Notice also that L2 is to be excluded from becoming a missile base because not visible from the Earth (the Moon hides it) and because we'll show later the L2 will better being kept free of radio-emitting devices to allow optimal SETI be done from the farside of the Moon (see Sections 4 and 5 of this paper). The selection of the colinear Lagrangian points L1 and L3 as space bases for missiles is now self-evident: they ensure the ***cylindrical symmetry of the problem around the Earth-Moon axis***. So, the direction in space from which the impactor is arriving towards the Earth becomes ***irrelevant*** (at least in this first-order approximation): we will just be studying confocal orbits in the plane passing through the Earth-Moon axis and the impactor. Additionally, the merit of all the Lagrangian points is that they are "fixed" in the Earth-Moon system, in that they keep their positions unaltered with respect to the Earth and the Moon at all times.
4) But being confocal, the missile's ellipse is automatically ***orthogonal*** to the impactor's hyperbola, meaning that the collision of the missile with the impactors always occurs at a right angle with the impactor's path. This is really ***<u>the best</u>*** we can hope for in order to deflect the impactor, since the missile's ***<u>full</u>*** momentum is then transferredto the impactor ***sidewise***.
5) Finally, if one missile fails to deflect the impactor's path in a sufficient amount, we can always send one or more missiles again along the new ellipse that is confocal to the new and slightly deflected impactor's hyperbolic path. This is because confocal conics are actually two ***families*** of ∞^1 trajectories. So, once again, the mathematical represention of the trajectories in the game by virtue of ***confocal*** conics matches perfectly with the physical problem of diverting impactors and comets!

3. Impactor-Confocal Ellipses for Missiles Shot from L3

Having ascertained the above five facts, we now face a mathematical problem: given the trajectory of the incoming impactor, that is given its confocal hyperbola, can the relevant confocal ellipse departing from L3 or L1 be determined uniquely ? Yes - is the answer - as we now prove with regard to missiles shot from L3.

Start from the polar equations, of the ellipse $r_{ell} = \dfrac{a_{ell}\left(1 - e_{ell}^2\right)}{1 + e_{ell}\cos\left(\theta_{ell} - \omega_{ell}\right)}$ (2.11) and of the hyperbola $r_{hyp} = \dfrac{a_{hyp}\left(e_{hyp}^2 - 1\right)}{1 + e_{hyp}\cos\left(\theta_{hyp} - \omega_{hyp}\right)}$ (2.12). The problem's given data is the impactor's hyperbolic path, whose three elements a_{hyp}, e_{hyp} and ω_{hyp} are here supposed to have been previously determined by astronomical observations and/or by radar detection to a sufficient accuracy. The problem's unknowns are the three elements a_{ell}, e_{ell} and ω_{ell} of the elliptical missile trajectory confocal (and so authomatically orthogonal) to the impactor's hyperbola and leaving from one of the three colinear Lagrangian points. In other words, we have to find three unknowns, and so we need three equations relating them. These three equations are:

1) The confocality condition (2.8), that holds just the same in both cartesian and polar coordinates.
2) The fact that we use only one branch of the hyperbola rather than both branches. This only branch is the one whose apsis is "facing" the confocal ellipse's apsis around the common focus, so these two apses are located on the ***opposite*** sides of the focus, namely on the opposite sides of the Earth. In mathematical terms, this description amounts to saying that the argument of the perigee of the ellipse differs from the argument of the perigee of the hyperbola exactly by an angle of 180°, that is $\omega_{ell} = \omega_{hyp} + \pi$ (2.13).
3) The third equation translates the requirement that the missile base has been located at either of the colinear Lagrangian points L1 and L3. To fix ideas, suppose that this point is L3 (the point "on the far opposite direction to the Moon" in Figure 1) and denote by R_{L3} the distance between the Earth and L3 (obviously known). The polar coordinates of L3 are then $\left(R_{L3}, \pi\right)$ and the requirement that the missile is launched from L3 translates in replacing these coordinates inside the polar equation of the ellipse (2.11), yielding

$R_{L3} = \dfrac{a_{ell}\left(1 - e_{ell}^2\right)}{1 + e_{ell}\cos\left(\pi - \omega_{ell}\right)}$ (2.14). The remaining calculations are just all the reductions necessary to solve the three simultaneous equations (2.8), (2.13) and (2.14) with respect to the three unknowns a_{ell}, e_{ell} and ω_{ell}.

But (2.13) is already solved for θ_{ell} . So, we simply replace (2.13) into (2.14), and get $R_{L3} = \frac{a_{ell}\left(1 - e_{ell}^2\right)}{1 + e_{ell}\cos\left(\theta_{hyp}\right)}$ (2.15). Next we must solve the remaining two simultaneous equations (2.8) and (2.15) for a_{ell} and e_{ell} . Then, replacing (2.8) into (2.15), one gets a second degree algebraic equation in the only unknown e_{ell} that we are not going to write here. Solving this equation for e_{ell} , one finds two roots, one of which must be discarded since negative. The other root, positive, is the requested expression for the eccentricity of the ellipse :

$$e_{ellL3} = \frac{\sqrt{R_{L3}^2 + 4 R_{L3}\, a_{hyp}\, e_{hyp} \cos\left(\theta_{hyp}\right) + 4 a_{hyp}^2\, e_{hyp}^2} - R_{L3}}{2\left[R_{L3}\cos\left(\theta_{hyp}\right) + a_{hyp}\, e_{hyp}\right]} . \tag{2.16}$$

This, replaced into the confocality condition (2.8), finally yields the semi-major axis of the ellipse

$$a_{ellL3} = \frac{\sqrt{R_{L3}^2 + 4 R_{L3}\, a_{hyp}\, e_{hyp} \cos\left(\theta_{hyp}\right) + 4 a_{hyp}^2\, e_{hyp}^2} + R_{L3}}{2} . \tag{2.17}$$

and the problem is solved. The position of the point of collision between the missile and the impactor is found as by-product by firstly replacing (2.16) and (2.17) into the equation of the ellipse (2.11), that yields the anomaly of the collision point. Replacing this anomaly into the hyperbola (2.12), one finally obtains the distance of the collision point from the Earth. Figure 3 shows a first numerical example (in arbitrary units not to scale with the actual Earth-Moon system values): the incoming impactor's is missing the Earth (represented by the larger circle located at the origin), but is of course deflected along an hyperbola. Then the missile shot from the Lagrangian point L3 (the smaller circle on the left) can hit the impactor before it approaches the Earth, colliding with it at an orthogonal angle.

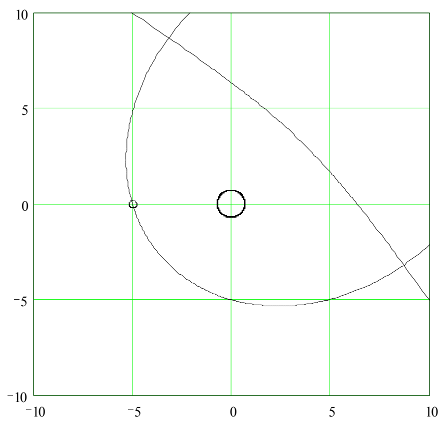

Figure 3.
Impactor missing the Earth, and elliptical path of the missile shot against it from L3.
The orthogonality of the two paths at their collision point is evident.

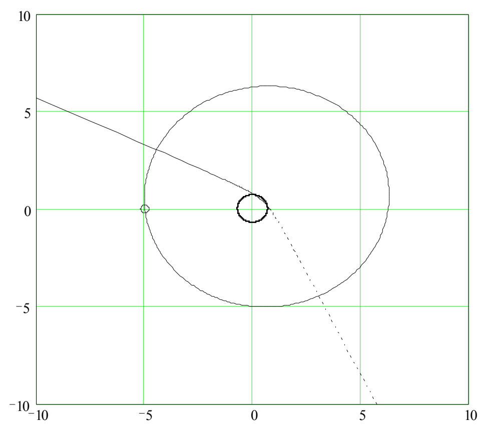

Figure 4.
Impactor hitting the Earth. Before it reaches the Earth, it could be diverted by the collision of a missile shot from L3 along the shown ellipse, orthogonal to the the impactor's path for the maximum deflection.

Finally, Figure 4 shows the feared impactor's impact against the Earth. But a missile shot from the Lagrangian point L3 along the shown ellipse, confocal to the impactor's hyperbola, could have rescued humankind beforehand!

4. Impactor-Confocal Ellipses for Missiles Shot from L1

All equations given in Section 3 deal with an impactor arriving "from the left" in Figure 1, that is arriving within the half-space delimited by a plane centered at the Earth, orthogonal to the Earth-Moon Axis, and ***not*** containing the Moon. This may be called the "Opposite to the Moon Half Space". If, on the contrary, the impactor arrives “from the right” in Figure 1, namely withing the half-space including the Moon, then the equations of the missile ellipse shot from L1 are slightly different. They are published here for the first time:

$$e_{ellL1} = \frac{\sqrt{R_{L1}^2 - 4 R_{L1} a_{hyp} e_{hyp} \cos(\theta_{hyp}) + 4 a_{hyp}^2 e_{hyp}^2} + R_{L1}}{2\left[R_{L1} \cos(\theta_{hyp}) - a_{hyp} e_{hyp}\right]} \qquad a_{ellL1} = \frac{\sqrt{R_{L1}^2 - 4 R_{L1} a_{hyp} e_{hyp} \cos(\theta_{hyp}) + 4 a_{hyp}^2 e_{hyp}^2} + R_{L1}}{2}$$

5. After the First Deflection: the Deflected Impactor’s New Hyperbola

This section provides ***some hints*** about the computation of the impactor’s ***new*** hyperbolic path ***after*** the first deflection occurred. In order to make it clear that the deflection occurs when the missile crashes against the impactor, we shall call this “the crash”, rather than the “missile-impactor impact”. Well, the spirit of this calculation is that the new after-crash speed is known because both the impactor’s and missile’s speed are known. Then, from the impactor after-crash speed, the new impactor’s hyperbola’s semi major axis is computed. The commonality condition then yields the relevant after-crash hyperbola’s eccentricity, and this completes the picture after the first crash. If more than one missile is launched, then at each new crash the new impactor hyperbola’s eccentricity will increase slightly, until the impactor’s perihelion distance will become higher than the Earth radius, thus avoiding the final impact against the Earth.

6. Political Problems for Planetary Defense from the Lagrangian Points

The Cold War ended about ten years ago, but many people’s minds are still too much in the Cold War attitude. Since nuclear weapons in space are forbidden by international treatises, a Proposal to locate missiles with possible nuclear warheads at the Lagrangian points L3 and L1 would immediately be perceived as an attempt to revive the Cold War. So, it is realistic to take for granted that any such a Proposal, if put forward officially to any country’s political institutions, would immediately be rejected by politicians as well as by the public at large. Just think of all the problems that NASA and ESA are having with ecologists just in order to put Radioactive Thermal Generators (RTGs) aboard their spacecrafts. Ecologists against RTGs actually support a narrow-minded view of ecology, based on the oversimplified belief that whatever is “nuclear” is “dangerous”. This is the heritage of the Cold War and of all wars that went before it.

Still the problem of doing Planetary Defense from space does exist.
The threat of impactors creating havoc on the Earth’s surface is a real threat, as it was quite well proven by the Tunguska event of 1908. However, (fortunately!) the Tunguska disaster took place in a lonely forest of Siberia, and so there were no casualties, and, on the other hand, back in 1908 not even the scientific community was ready to accept that such an disaster could possibly occur, not to mention that governments and lay people were not ready at all to learn the Tunguska lesson. So, everyting went on just as if nothing had happened at Tunguska, until the first scientists took some notice in 1927.

All this shows well that humankind still is not yet ready to face the threat of impactors and comets. Only when humans will stop planning and conducting big wars among themselves, will the governments have more time to think about the new danger coming from space. And ecologists will get mature to the point of not hampering their governmental agencies to put up missiles and weapons in space if these are to prevent dangerous asteroids and comets from killing the whole of humankind, including the ecologists themselves!

In conclusion, this new ***conscience of a single fate for the whole of humankind*** will sooner or later take over in the vast majority of humans, and prepare them to the deep changes of new millenium.

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COMET/ASTEROID PROTECTION SYSTEM (CAPS): A SPACE-BASED SYSTEM CONCEPT FOR REVOLUTIONIZING EARTH PROTECTION AND UTILIZATION OF NEAR-EARTH OBJECTS.

D. D. Mazanek, NASA Langley Research Center, MS 328, Hampton, VA 23681-2199, USA. d.d.mazanek@larc.nasa.gov

There exists an infrequent, but significant hazard to life and property due to impacting asteroids and comets. Earth approaching asteroids and comets are collectively termed NEOs (near-Earth objects). These planetary bodies also represent a significant resource for commercial exploitation, long-term sustained space exploration, and scientific research. The goal of current search efforts is to catalog and characterize by 2008 the orbits of 90% of the estimated 1200 near-Earth asteroids larger than 1 km in diameter. Impacts can also occur from short-period comets in asteroid-like orbits, and long-period comets which do not regularly enter near-Earth space since their orbital periods range from 200-14 million years. There is currently no specific search for long-period comets, smaller near-Earth asteroids, or smaller short-period comets. These objects represent a threat with potentially little or no warning time using conventional terrestrial-based telescopes. It is recognized, and appreciated, that the currently funded terrestrial-based detection efforts are a vital and logical first step, and that focusing on the detection of large asteroids capable of global destruction is the best expenditure of limited resources. While many aspects of the impact hazard can be addressed using terrestrial-based telescopes, the ability to discover and provide coordinated follow-up observations of faint and/or small comets and asteroids is tremendously enhanced, if not enabled, from space. It is also critical to ascertain, to the greatest extent possible, the composition and physical characteristics of these objects. A space-based approach can also solve this aspect of the problem, both through remote observations and rendezvous missions with the NEO. A space-based detection system, despite being more costly and complex than Earth-based initiatives, is the most promising way of expanding the range of objects that could be detected, and surveying the entire celestial sky on a regular basis. Finally, any attempt to deflect an impacting NEO with any reasonable lead-time is only likely to be accomplished using a space-based system.

This poster presentation provides an overview of the Comet/Asteroid Protection System (CAPS) - a future space-based system concept that provides integrated detection and protection through *permanent*, *continuous* NEO monitoring, and *rapid*, *controlled* modification of the orbital trajectories of selected comets and asteroids. The goal of CAPS is to determine whether it is possible to identify a "single" orbiting or lunar based system concept to defend against the entire range of threatening objects, with the ability to protect against 1 km class long-period comets (including inactive nuclei) as the initial focus. CAPS would provide a high probability that these objects are detected and their orbits accurately characterized with significant warning time, *even upon their first observed near-Earth approach*. The approach being explored for CAPS is to determine if a system capable of protecting against long-period comets, placed properly in heliocentric space, would also be capable of protecting against smaller asteroids and comets capable of regional destruction.

The baseline detection concept advocates the use of large aperture (≥ 3 meters), high-resolution telescopes capable of imaging in the ultraviolet, optical, and infrared wavelengths. Coordinated telescope control for NEO surveying and tracking would be incorporated to maximize follow-up observations, and baffling and/or shading would be employed to permit observations close to the Sun. Each telescope would have large area mosaic detector arrays (approximately 36K $\times$ 36K pixels), with the survey telescopes having a 1.0 $\times$ 1.0 deg. FOV and the tracking telescopes having a 0.1 $\times$ 0.1 deg. FOV. Spectral imaging would be implemented as early as possible in the detection process. Advanced detectors capable of rapid identification of NEOs and their spectral signal could greatly simplify operations and minimize the requirements on the tracking telescopes. If NEOs could be uniquely identified in multiple survey images, a preliminary orbit could be determined with minimal risk of "losing" the object. The tracking telescopes would be used in an interferometric mode when higher precision astrometric observations are needed to confirm an object has an impacting trajectory. Finally, active laser ranging could be used to provide range and range-rate data to augment precision orbit determination. Active laser ranging is preferable to radar systems due to the potentially large distances between the target and the detection system. The tracking telescopes could be used as receivers for the laser ranging system, or the return signal of faint NEOs could be enhanced through active illumination to aid in interferometry measurements.

The primary orbit modification approach uses a spacecraft that combines a multi-megawatt power system, high thrust and specific impulse propulsion system for rapid rendezvous, and a pulsed laser ablation payload for changing the target's orbit. This combination of technologies may offer a future orbit modification system that could deflect impactors of various compositions without landing on the object. The system could also provide an effective method for altering the orbits of NEOs for resource utilization, as well as the possibility of modifying the orbits of smaller asteroids for impact defense. It is likely that any NEO defense system would allow for multiple deflection methods. Although laser ablation is proposed as the primary orbit modification technique, alternate methods, such as stand-off nuclear detonation, could also be part of the same defensive scenario using both rendezvous and intercept trajectories. Advanced technologies and innovation in many areas are critical in adequately addressing the entire impact threat. Highly advanced detectors that have the ability to provide the energy and time of arrival of each photon could replace current semiconductor detectors in much the same way as they replaced photographic plates. It is also important to identify synergistic technologies that can be applied across a wide range of future space missions. For example, technologies permitting humans to traverse the solar system rapidly could be highly compatible with the rapid rendezvous or interception of an impactor. Likewise, laser power beaming (visible, microwave, etc.) may be applicable for space-based energy transfer for remote power applications, as well as NEO orbit modification.

The vision for CAPS is primarily to provide planetary defense, but also provide productive science, resource utilization and technology development when the system is not needed for the infrequent diversion of impacting comets and asteroids. The vision is for a future where asteroids and cometary bodies are routinely moved to processing facilities, with a permanent infrastructure that is capable and prepared to divert those objects that are a hazard. There is tremendous benefit in "practicing" how to move these objects from a threat mitigation standpoint. Developing the capability to alter the orbits of comets and asteroids routinely for non-defensive purposes could greatly increase the probability that we can successfully divert a future impactor, and make the system economically viable. It is likely that the next object to impact the Earth will be a small near-Earth asteroid or comet. Additionally, a globally devastating impact with a 1 km class long-period comet will not be known decades, or even years, in advance with our current detection efforts. Searching for, and protecting ourselves against these types of impactors is a worthwhile endeavor. Current terrestrial-based efforts should be expanded and a coordinated space-based system should be defined and implemented. CAPS is an attempt to begin the definition of that future space-based system, and identify the technology development areas that are needed to enable its implementation. Finally, it is fully appreciated that at the present time space systems are much more costly than terrestrial-based systems. Hopefully, this will change in the future. Regardless, understanding what it would take to defend against a much wider range of the impact threat will foster ideas, innovations, and technologies that could one day enable the development of such a system. This understanding is vital to provide ways of reducing the costs and quantifying the benefits that are achievable with a system like CAPS.

DETERMINING HIGH ACCURACY POSITIONS OF COMETS AND ASTEROIDS. A. K. B. Monet, *US Naval Observatory Flagstaff Station, Flagstaff, AZ 86002 (alice@nofs.navy.mil)*.

Beginning in 1991 with the Galileo spacecraft encounter with Gaspra, the USNO Flagstaff Station has been providing highly accurate astrometry of comets and asteroids to NASA/JPL in support of a variety of missions and observing efforts. Over the years, no effort has been spared to attain the greatest possible accuracy. This has led to improvements in hardware, detectors, supporting electronics, observing strategies, astrometric analysis, and – perhaps most significantly – in astrometric reference catalogs. USNO is proud to have contributed to the many successful encounters, flybys, radar ranging experiments, and improved orbits for targets of particular interest. While each solar system body seems to present its own peculiar observing challenges, we have developed a certain level of confidence in our astrometric methods. If an object is detectable with our instrumentation, we can accurately determine its position.

In this report, I discuss what we have come to regard as the key elements in a successful astrometric campaign. These include a wide field of view and target-appropriate centroiding algorithms. Perhaps the most important is an accurate, dense, reference catalog of faint objects. In recent years, the Naval Observatory has produced a number of such catalogs – most notably the USNO-A2.0 catalog and the UCAC. The 8-inch FASTT telescope has also been used to densify regions of the TYCHO catalog, for particular applications. At the time of this Workshop, new versions or expansions to these existing catalogs are under development, and new survey programs are being planned which will yield yet-more accurate and dense reference grids. All of these factors contribute to improved accuracy for asteroid and comet positions. Certainly, the accuracy of the astrometric positions is one of the essential ingredients in the effort to identify those comets and asteroids which pose a potential threat to our planet.

Lesson #1: Optimize target placement

Ideally, observations will be made when targets are:

- well-separated from background stars, galaxies and bright foreground objects,
- at least 30° above the horizon, and
- more than 20° from the galactic plane.

This can be accomplished by plotting the asteroid's or comet's path on a star chart. A necessary prerequisite for this task is an accurate ephemeris. An excellent resource for ephemerides is the JPL "Horizons" program, available on the web at

http://ssd.jpl.nasa.gov/horizons.html

An all-sky star chart program, utilizing the USNO-A2.0 and ACT catalogs, resides at

http://www.nofs.navy.mil/data/fchpix/

Lesson #2: Round images are best.

A trailed image in a field of round star images is an unmistakable indicator of a moving object. Our experience, however, has indicated that centroiding and accurate astrometry are more reliably achieved with round images. Since our emphasis is on astrometry, rather than detection, we select exposure times that will yield round images.

Centroiding essentially involves finding the locus of the peak in the gradients of an image in two orthogonal coordinates. A round, properly focussed image will generally have one central peak (the exception being comets, discussed later.) A trailed image will have a peak in the cross track direction, but only the endpoints contribute to the astrometric signal in the direction of trailing.

In the time required to take a trailed exposure, it is possible to take a series of short exposures, producing a series of round images. We used this technique for astrometry of the Galilean moons, in support of the Galileo mission. This allowed the computation of several accurate positions for each moon over the period of observation each night. Accomplishing multiple exposures closely spaced in time with a CCD camera can be done using the shutter and partial reads of the chip between exposures.

An alternative to this method is planned using the newest USNOFS CCD camera, now being built for the 1.3-meter telescope. This camera has been designed to track and integrate photons from a non-sidereal target while simultaneously providing a stellar reference frame. It will have a mosaic of six CCDs, one of which will clock the charge to match the motion of a non-sidereal object. The entire camera will be rotated to align this chip with the path of the target. The other chips will operate in stare mode and provide a well-guided image of the surrounding sky.

Lesson #3: Detect moving objects.

Detection of moving objects using only round images can be accomplished by a number of methods. Those used at USNOFS include:

- For a single exposure, use the ephemeris to predict the pixel coordinates of the target on the chip. Search for the object at that location and along the line-of-variations representing the most probable path of the object across the field. Comparison of the object coordinates with those of field stars from a reference catalog, which is complete to at least a few magnitudes fainter than the target, reduces false identifications.

- With multiple frames, line up the star images and look for objects that shift from one frame to the next. This is the traditional "blink" method, and is highly effective for images with very low SNR.

- Frame subtraction is possibly the most effective method, as it essentially eliminates all non-moving objects from consideration. It is especially useful when working in crowded fields such as the Galactic plane. Multiple frames are aligned, and one is subtracted from the others. All stationary objects will be erased, but those which move between exposures will remain, since the images of moving objects will not overlap.

The first method is employed for all FASTT observations, since the transit telescope can make only one observation per night of any given target. Both the blink and subtraction methods are far more sensitive, and much less prone to confusion. Multiple observations also provide a measure of the velocity of any moving objects in the field of view, which in turn gives a rough indication of the distance of the objects from the Sun.

A second benefit of the multiple frame approach is that detection of moving objects is relatively insensitive to changes in apparent brightness. As long as the target is visible in the images, its motion will be obvious, and variations in brightness will be useful additional data. But in single frame detection, the magnitude is needed to distinguish the target from background objects. In this case, variations in brightness increase uncertainty.

Lesson #4: Minimize confusion.

A moving object detection method will detect anything that moves in the field of view during an exposure – not just the target. This can lead to confusion in identification of the target object. With USNOFS cameras, images tend to be somewhat over-sampled. For example, the pixel scale of the 2K$\times$2K camera on the 61-inch telescope is 0.33 arcsec/pixel. Typical seeing at USNOFS would be 1-2 arcsec FWHM. Thus, an image normally spans several pixels. This over-sampling means that celestial objects generally appear quite different than cosmic rays and other non-celestial "defects" in a frame.

It is possible, particularly in fields along the ecliptic, to have more than one asteroid or comet appear in the same frame. Utilities exist on the web to show all known comets and asteroids which will pass through a given field of view during a particular time interval. One of these is provided by Bruce Koehn at Lowell Observatory, at:

http://asteroid.lowell.edu/cgi-bin/koehn/astplot

The IAU Minor Planet Center also provides a "Minor Planet Checker", which lists known asteroids in a given field of view.

http://cfaps8.harvard.edu/ cgi/CheckSN.COM

Lesson #5: Tailor centroiding method to target.

With properly-timed exposures, asteroid images may closely resemble stars, so the centroiding methods developed for stars may be used with confidence. As with stars, the wise will avoid using using flux-weighted means to find the image centroids. Our experience has shown that fitting 1-dimensional Gaussians to the marginal distributions is both fast (hence, cheap) and effective.

Comets certainly do not resemble stars, and can be very messy indeed. A case in point was the campaign last year to provide astrometry of comet 19P/Borrelly prior to the DS1 flyby. A number of observers participated in this effort. At the USNO Flagstaff Station, observations were made with two different telescopes. All observations were reduced independently by Ron Stone and the author, using different centroiding algorithms but the same reference catalog. The resulting positions differed systematically, but no errors were found that would account for the differences. So both sets of positions were reported to the navigation team at JPL. When data obtained from the spacecraft were compared to ground-based astrometry, it was noted that centroids based on the "hottest pixel" in the comet image showed significantly smaller bias relative to centroids based on Gaussian fits to a stellar PSF. The problem was that the comet's image was highly asymmetric and the PSF fitting methods could not account for this distortion (see figure). While the "hot pixel method" might not yield the highest accuracy for all comets, the Borrelly experience strongly suggests that it should be part of the astrometrist's toolbox.

Lesson #6: Use the best available reference catalog!

We determine astrometric coordinates of solar system bodies by computing their positions relative to background stars. It is therefore desirable for the reference star catalog meet the following criteria:

- Individual star positions should have good precision, with minimal zonal or systematic errors.
- The catalog should be tied to the International Celestial Reference System (ICRS)
- The density of catalog stars must be sufficient to insure a good reference frame in any field of view. (For the 61-inch telescope, this means a density of roughly 300 stars per sq degree.)
- The reference catalog must be reasonably complete in the magnitude range of the target objects to be useful for distinguishing between targets and background objects.

In recent years, we have come to rely on two reference catalogs for nearly all solar system astrometry: the USNO-A2.0 catalog and the UCAC (USNO CCD Astrograph Catalog). The USNO-A covers the entire sky with an accuracy of $\pm$180 mas and is nearly complete to magnitude 19. The UCAC covers the entire southern sky and will eventually provide full-sky coverage. Its accuracy is $\pm$20 mas for the 10-14 magnitude range and it has a limiting magnitude of 16. (New versions of both catalogs are about to be released. See the accompanying handouts.)

Lesson #7: Match observing cadence to application.

In the best of all possible worlds, those in the business of computing the orbits of potential Earth impactors would have available to them an infinite supply of high-accuracy astrometric positions from many nights of observing covering a large portion of each target's orbit. In the real world, however, observing time for astrometry is fairly limited. On the best telescopes at the best observing sites, it's a highly-prized and scarce commodity. It is only reasonable then to time observations for maximum value for orbit computation. It makes little sense, for example, to make 20 observations on a single night of a target whose orbit is uncertain, and then to ignore it for the next several months. Far better to make a couple of observations one night, a few more a week later, and perhaps another in a month or two – thus pinning down the orbit and greatly improving the accuracy of orbit predictions. Achieving the most efficient observing candence requires communication between astrometrists and the celestial mechanicians using their data. This cannot be emphasized too strongly!

INITIAL ORBITS FOR NEAR-EARTH OBJECTS FROM HIGH-PRECISION ASTROMETRY. K. Muinonen, *Observatory, University of Helsinki, P.O. Box 14, FIN-00014 U. Helsinki, Finland (Karri.Muinonen@helsinki.fi)*, J. Virtanen, *Observatory, University of Helsinki, P.O. Box 14, FIN-00014 U. Helsinki,Finland*, F. Mignard, *Observatoire de la Cote d'Azur, CERGA, UMR CNRS 6527, av. Copernic, F-06130 Grasse, France*.

We are studying the effects of high-precision astrometric observations on the computation of near-Earth object (NEO) orbits and collision probabilities. In addition to standard astrometry, we are examining differential astrometry, that is, either differences of two positions from standard astrometry or the actual sky-plane motion. GAIA, the next astrometric cornerstone mission of ESA, is due for launch no later than 2011. The duration of the GAIA survey will be 5 years, the limiting magnitude equals V = 20 mag, and full sky will be covered some dozen times a year. In particular, GAIA promises to provide an unprecedented NEO search across the Milky Way area typically avoided by groundbased searches. The extraordinary precision of the astrometry, varying from 10 micro-arcseconds at V = 15 mag to a few milliarcseconds at V = 20 mag, will have a major impact on NEO orbit computation, in particular, on the derivation of NEO collision probabilities and the assessment of the collision hazard. In addition to standard positional astrometry, GAIA will obtain differential astrometric observations: it promises to detect an object's motion across the field of view. The accuracy of the GAIA astrometry imposes a challenge for orbit computers, as an NEO's size, shape, and surface properties will have an effect on the astrometry. This effect will depend on the NEO orientation with respect to the Sun-NEO-GAIA plane and, in particular, on the solar phase angle (the angle between GAIA and the Sun as seen from the NEO). We show tentative simulations about the improvement of NEO orbits by precise astrometry. Finally, we show predicted NEO detection statistics for the GAIA mission.

We study the inverse problem of deriving asteroid orbital-element probability densities from given astrometric data sets. Our goal is to extend the Bayesian treatment of standard astrometry by Muinonen & Bowell (1993) to incorporate differential astrometry. In particular, we are interested in short observational arcs and small numbers of observations, and are making use of the statistical ranging technique throughout the present paper (Virtanen et al. 2001, 2002; Muinonen et al. 2001, 2002; see also Muinonen 1999). For a current review of advances in asteroid orbit computation, see Bowell et al. (2002) and, for the future ESA astrometric cornerstone mission GAIA, see, e.g., Mignard 2002; Perryman et al. 2001.

To study the influence of high-precision astrometry on orbital accuracy, we applied the ranging technique to the near-Earth asteroid 1998 OX_4. By gradually decreasing our assumption of observational noise, i.e., increasing the astrometric accuracy, we computed the orbital-element probability densities using theoretical least-squares positions as sets of "corrected" observations. Since we also wanted to answer the question "what is the minimum number of high-precision observations needed to improve the orbit significantly?", we began with the minimum requirement, that is, two astrometric observations per object.

For the Earth-crossing asteroid 1998 OX_4, observations covered only a 9.1-day arc, with altogether 21 observations on 6 nights. Furthermore, there were non-vanishing collision probabilities in several close approaches after year 2012. The asteroid was serendipituously recoved in summer 2002.

We chose two observations separated by 3.0 hr on the second night. The choice of the time span was motivated by the GAIA scanning law with a spin rate of 3 hr and a corresponding time difference between repeated observations on a given object. We applied ranging to the set of two observations and tested a sequence of observational noise values: σ =(0.5 as, 50 mas, 5 mas, 0.5 mas, 50 μas). However, it turned out that, at least for two closely spaced observations, increasing the accuracy of the observations does not provide any major constraint on the orbital element distribution. The phase-space region of possible solutions spreads over hundreds of AU in semimajor axis and from 0 to 1 in eccentricity regardless of the assumption of observational errors.

We then added a third observation in between the two previously used, and repeated the analysis. The extent of the marginal distributions in (a, e)-plane in Figs. 1 and 2 show that obtaining a third observation of an object is crucial in terms of orbital accuracy at least for this case. For 1998 OX_4, a major improvement of the orbital elements takes place between 5 mas and 0.5 mas. In fact, the results indicate that there is a threshold value for the astrometric accuracy below which the orbital-element probability density becomes well confined, although the exact value of the threshold seems to be case-sensitive.

Finally, we repeated the analysis for four simulated observations: two pairs of close-by observations with a 20-second time difference separated by 3.0 hr. This time the orbital improvement takes place after the observational noise has been diminished to 50 μas (Fig. 3). This indicates that, if three more loosely-spaced observations cannot be obtained within the GAIA spin period, such a set of observations would prove useful for orbit improvement, presuming astrometric accuracy of at least 50 μas.

Table 1 summarizes the predicted NEO detection statistics for the GAIA mission (Mignard 2002). The simulations indicate that most of the faint objects will cross the field of view undetected; for an object of absolute magnitude $\sim$18, the probability that it will be observed repeatedly by GAIA is roughly half.

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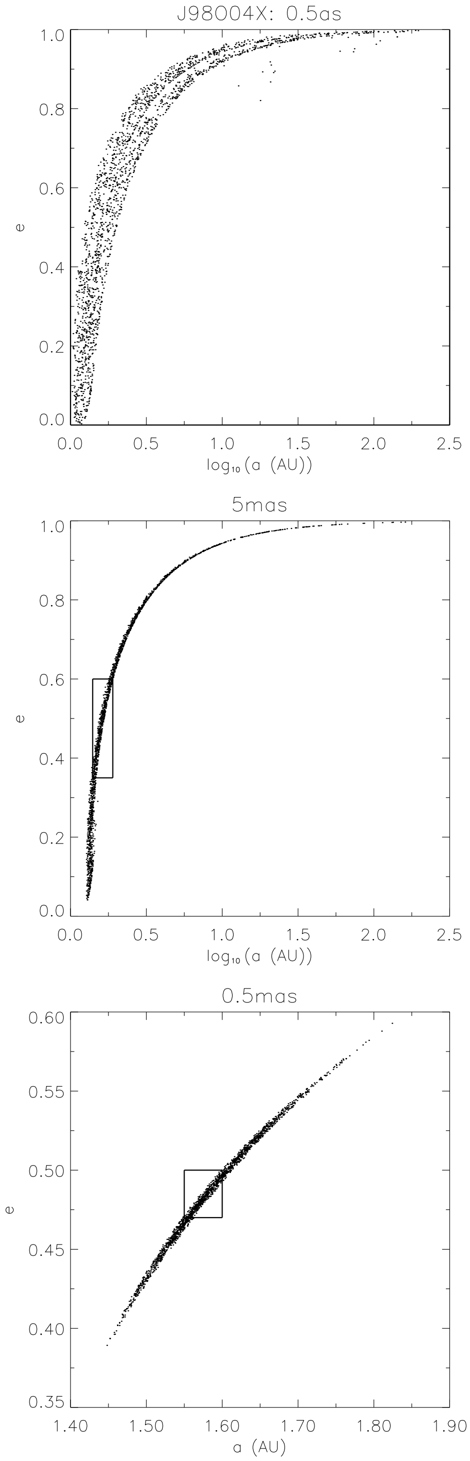

Figure 1: Gradual improvement of the semimajor axis-eccentricity probability density with improving accuracy for 1998 OX_4. From top to bottom, we show the extent of the marginal probability densities for σ =0.5 as, 5 mas, and 0.5 mas. The boxes in the upper plots indicate the extents of the corresponding plotting windows below, while the box in the lowermost plots refers to the upper plot in Fig. 2.

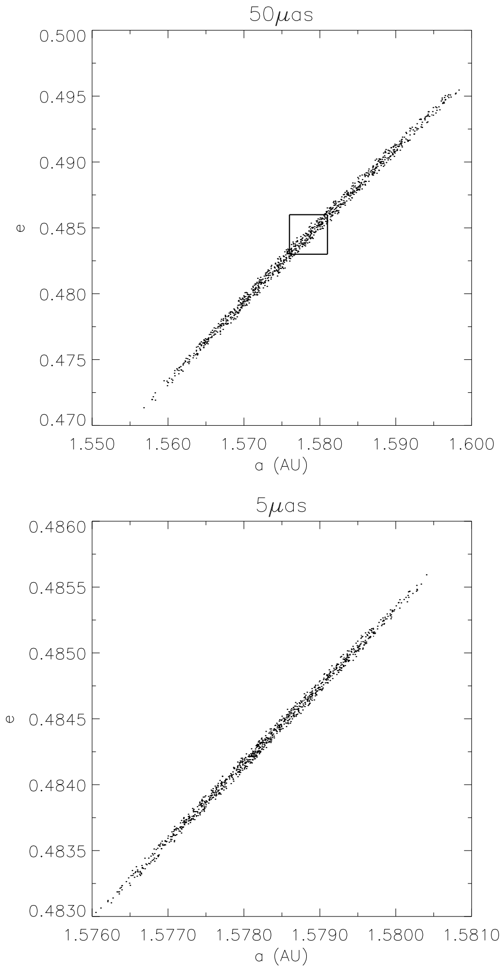

Figure 2: As in Fig. 1 but for σ =50 μas, and 5 μmas.

Table 1: Probability of observing an NEO of a given absolute magnitude H with GAIA. The columns gives the probability that repeated observations occur a certain number of times, from $n = 0$ (never observed) to $n > 25$. The numbers add to 100 percent along a line. A limiting magnitude $V = 20$ has been adopted for the detection.

H	$n = 0$	$1 < n \leq 10$	$10 < n \leq 25$	$n > 25$
	%	%	%	%
14	2	1	6	91
15	5	4	15	76
16	11	9	25	55
17	19	18	30	33
18	40	27	21	12
19	73	21	4	2
20	89	9	2	0
21	96	3	1	0

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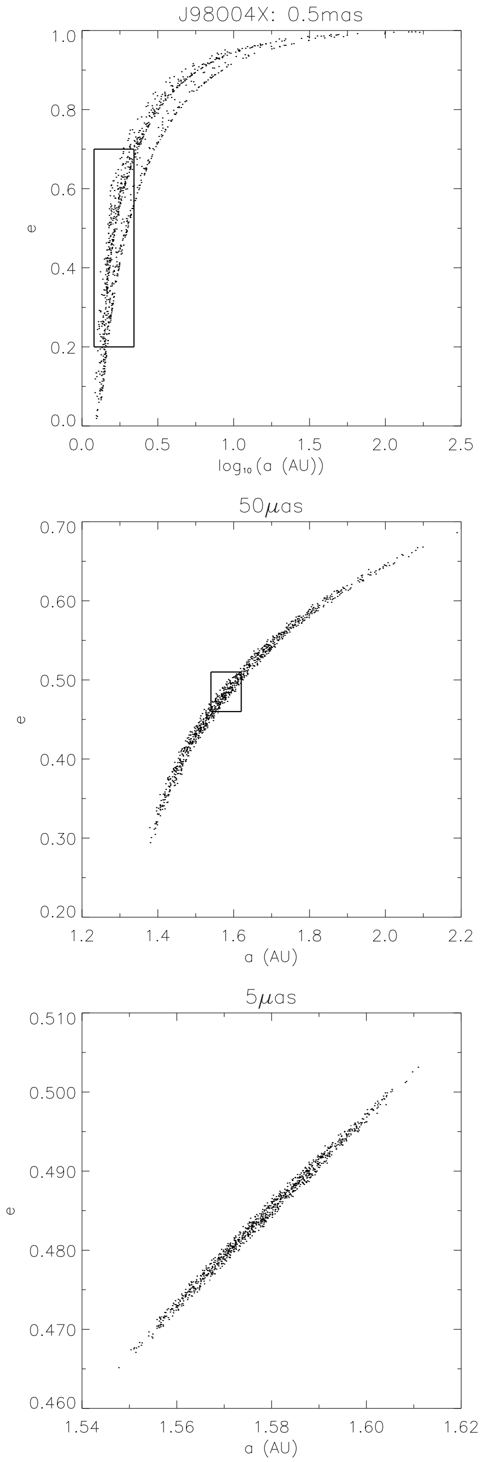


Figure 3: Gradual improvement of the semimajor axis-eccentricity probability density with improving accuracy for four simulated astrometric observations of 1998 OX_4 (two pairs of close-by observations with a 20-second time difference separated by a few hours). From top to bottom, we show the extent of the marginal probability densities for σ =0.5 mas, 50μas, and 5μas. The boxes in the two uppermost plots indicate the extents of the corresponding plotting windows below.

Communicating about Cosmic Catastrophes

Brendan M. Mulligan, *CIRES, Univ. Colorado (Boulder) & Queen's Univ. (Hamilton)*

Clark R. Chapman, *Southwest Research Inst. (Boulder)*

Introduction

The history of the Earth, and all the bodies in the solar system, has been marked by cosmic catastrophes of epic proportions: impacts due to asteroids and comets. Large-scale impacts have occurred in the past and, despite a decline in impact flux, the potential for future impacts constitutes a legitimate threat to human civilization. Communicating about the risk that near-Earth objects (NEOs) pose to the general public presents a serious challenge to the astronomical community. Although the NEO hazard has a unique character, comparisons with other natural hazards can readily be drawn and lessons can certainly be learned from years of experience that other researchers have in risk communication.

Just as specialists dealing with other hazards have done, the NEO community has addressed the challenge of risk communication by developing tools, most notably the Torino Impact Hazard Scale, capable of conveying useful information to a diverse audience. Numerous researchers and commentators have critiqued the scale, some suggesting modifications or proposing particular significant revisions. These critiques have dominantly focused on the Scale's perceived technical weaknesses, neglecting the central issues concerning its ability to inform the public in a satisfactory way.

For instance, an issue that has already been dealt with in other cases (e.g. the "terrorism scale" of the U.S. Dept. of Homeland Security) concerns the degree to which the wording in the public scale tells people what they should specifically do in response to a particular warning level. The American Red Cross, for example, tabulated different responses that might be appropriate for different groups (individuals, families, neighborhoods, schools, and businesses) as to how they should respond to a particular level of threat. Similar clarification of the Torino Scale might be in order. We hardly expect the public to "carefully monitor" an NEO predicted as having a Torino Scale "1" close encounter; those words were intended for astronomers. But given recent hype in popular media concerning 2002 NT7, further clarification for science journalists about appropriate levels of response for different interest groups (astronomers, space agency or emergency management officials, ordinary citizens) might be appropriate.

The NT7 Event

In late July 2002, the public was alarmed when many news media carelessly proclaimed a likely threat that an asteroid would strike the Earth a few decades hence and cause terrible destruction. The route from a routine asteroid discovery, to a technically interesting but publicly insignificant prediction of an extremely low probability impact, to a headline-making scare began with the unannounced posting on technical web sites of technical data about the asteroid 2002 NT7. Included on the web sites was a ranking on a technical hazard scale (the PTS) introduced a year earlier for technical analysis (it has negative and positive numbers, and decimal places).

Although most asteroid hazard researchers had agreed to use the 1-10 Torino Scale (NT7 falling near the boundary between 0 and 1, meaning "no concern") to communicate the seriousness of possible impact predictions, some purveyors of asteroid news (including the CCNet internet newsletter and prominent British and American news media) chose to emphasize that the NT7 event was the "first time" the PTS rating had a positive value. It was like calling the Queens air crash in autumn 2001 "the worst transportation disaster of the century" when the century was not even a year old!

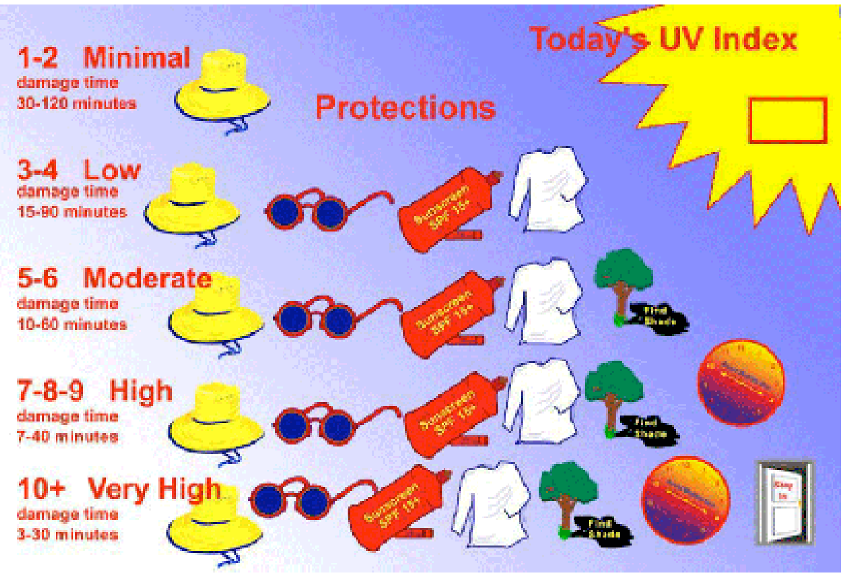
CNN switched its references from the PTS to the Torino Scale in a matter of hours. But subsequent news coverage remained confusing and inappropriate to the scientific realities. If all the scientists and journalists involved in NT7 had explained (once again!) the simple process whereby new observations of the asteroid were being used to refine the predictions, which would almost certainly go to zero probability within a few days, the story might instead have run on pg. 17, or not at all. We should save the drama for truly exceptional events, conceivably even including a future impact.

Other Hazard Scales

Astronomers are hardly the first scientists to encounter difficulties with hazard scales. We can learn from experiences in developing other scales. Just as two scales have confused communication of predicted asteroid impacts, multiple scales exist for other natural hazards. But, despite internal debates about how to announce an earthquake Magnitude and the existence of multiple seismic scales, the public has been shielded from such internal, technical dissension and has become quite comfortable with Magnitudes, even though the appellation "Richter" has officially disappeared.

The Richter Scale is familiar as a roughly 1-10 scale of earthquake strength. Developed by seismologist Charles Richter in the 1930s, people in California are well-calibrated to the numbers associated with their personal experiences. Educated people worldwide know that earthquakes less than 5 rarely make the news, and an 8 is something horrific. Yet there have been raging debates among seismologists, behind the scenes, about how to communicate with the public about the enormous differences between earthquakes separated by only a few numbers on the logarithmic scale. "Dare we discuss logarithms?" "What does the public understand about decimals, as in a 5.7 magnitude quake?" In reality, the Richter Scale (technically defined only for a particular instrument that saturated well below the magnitudes of large earthquakes), has been officially abandoned. Official pronouncements, at least in the U.S., refer only to Magnitude. Fortunately, "Magnitudes" are similar to values on the "Richter Scale" and the public remains blissfully unaware of the internal dissension among seismologists. Asteroid astronomers would do well to follow this example. Few members of the attentive public will put up with debates about the scales. Long-term consistency must be the watchword.

There are many other scales, some familiar and some not-so-familiar, used by different scientific specialties to translate their technical findings or judgements into messages that ordinary citizens can relate to…and take appropriate action. They deal with topics as mundane as air quality and the dangers of UV on a sunny day to topics as vital as the end-of-the-world by nuclear war (e.g. the Doomsday Clock, of the *Bulletin of the Atomic Scientists*). Some other scales are esoteric; 8 separate "Space Weather Alert" scales are managed by NOAA's Space Environment Center. Changes were made to these space weather scales in March 2002; the chief users of these scales, however, are technical people, even though there may be public consequences (e.g. with radio transmission or even electrical power). How effectively scales are presented influence their acceptance and the influence they have on behavior. The familiar fire-danger scale (arrow pointing to colored zones of fire danger ranging from “low” to “extreme”) has been used for decades and is well known in the American West. The particular illustration of the UV Index (*below*) is especially effective at translating the numbers into practical actions that people can take to minimize their exposure to dangerous sunlight. Some scales have been adopted internationally (e.g. the International Nuclear [Reactor] Event Scale) while others are more *ad hoc*.



The Torino Scale

The scale itself is a linear, 0-to-10 scale, with associated colors and words. Some critics of the scale have advocated that it be 2- or 3-dimensional. But no other hazard scales are (or should be) presented to the public in such a fashion; even educated lay people rarely comprehend 2-D graphs. The 2-dimensional plot of the Torino Scale familiar to asteroid researchers is a technical definition of how the Torino Scale values for a predicted potential impact are calculated from two quantities: the impact energy and the probability of impact. The technical version is not intended for public presentation, but for use by scientists and science communicators.

The even more complex Palermo Technical Scale (PTS) was devised for use by impact hazard experts. The scale is a one-dimensional scale (a range of numbers to several significant figures, with no beginning or end, spanning zero) calculated from the same two quantities used to calculate values on the Torino Scale plus a third quantity: the time until the predicted event.

Some have argued that the Torino Scale would be more “elegant” if it were calculated more like the PTS. In fact, there is a rough one-to-one mapping between PTS values and Torino Scale values. Indeed, the Torino Scale could be defined as = PTS +2.5 (rounded to the nearest integer, or 0 for all negative values), and its values would usually not vary by 1 unit in the important lefthand part of the diagram, or in color in the righthand part. Perhaps the definitions of the Torino Scale could be tweaked behind-the-scenes without damaging either the consistency or credibility of the scale in its public representation. In its first 4 years, the Torino Scale has gained fairly widespread use by science journalists worldwide. Its use should continue to be encouraged. Perhaps implementation of our suggestions could avoid future confusions like the one that fueled the recent NT7 media hype.

Conclusions

Clearly, the NEO community’s efforts to help the public place in context any news about possible future impacts remain only partially effective; NEO impact predictions continue to be met with confusion, misunderstanding, and sensationalism. The Torino Scale value is not the only information about impacts available to the public and, indeed, scales of any sort are not the only way to bring some convergence into public discussion of particular predictions. Astronomers have a public responsibility to develop simple protocols for honestly but understandably communicating about the inherently tiny chances of potentially huge disasters that characterize the impact hazard. Drawing from experience with other scales, we advocate that the IAU and other players and entities develop policies grounded in previous experience that can ensure accuracy, consistency, and clarity in reports of impact predictions. Only if we get our scientific house in order can we demand responsibility on the part of the science communicators and journalists who constitute the next link in the chain of communication.

Asteroid experts are not the first to face difficulties in communicating the practical implications of their work to the public. We must consistently use the Torino Scale and other simple, honest ways to put our work and predictions into an understandable context. The Torino Scale itself can be improved (both in its public image and in behind-the-scenes definitions) in ways that don’t confuse the public.

RADAR RECONNAISSANCE OF POTENTIALLY HAZARDOUS ASTEROIDS AND COMETS.

S. J. Ostro[1], [1]Jet Propulsion Laboratory, California Institute of Technology (300-233, Jet Propulsion Laboratory, Pasadena, CA 91109-8099, ostro@reason.jpl.nasa.gov).

Groundbased radar is an intelligence-gathering tool that is uniquely able to reduce uncertainty in NEO trajectories and physical properties. A single radar detection secures the orbit well enough to prevent ìlossî of newly discovered asteroids, shrinking the instantaneous positional uncertainty at the object's next close approach by orders of magnitude with respect to an optical-only orbit. This conclusion, reached initially by [1] through Monte Carlo simulations, has been substantiated quantitatively by comparison of residuals for radar+optical and optical-only positional predictions for recoveries of NEAs during the past decade [2].

Integration of an asteroid's orbit is afflicted by uncertainties that generally increase with the length of time from epochs spanned by astrometry. Eventually the uncertainties get so large that the integration becomes meaningless. The duration of accurate orbit integration defines our window of knowledge about the object's whereabouts. Presumably we want to find out if any given NEO might threaten collision, and if so, we would like as much warning as possible. Radar extends NEO trajectory predictability intervals far beyond what is possible with optical data alone, often approaching the end of this millennium (e.g., 1999 JM8 [3]).

For 2002 FC, an eight-week arc of discovery-apparition optical astrometry could not reliably identify any close Earth approaches before or after 2002, but with Arecibo astrometry from May 24 and Goldstone astrometry from June 6 (the object's last radar opportunity until 2040), close approaches could be identified reliably during the 1723 years from 488 to 2211. At this writing, with a much longer, 3.3-month optical arc, the corresponding intervals are 1951 years with radar (464 to 2415) and 137 years without it (2002 to 2139).

For asteroid (29075) 1950 DA, analysis of the radar-refined orbit [4] revealed that there will be a possibly hazardous approach to Earth in 2880 that would not have been detected using the original half-century arc of pre-radar optical data alone. This event could represent a risk as large as 50% greater than that of the average background hazard due to all other asteroids from now through 2880, as defined by the Palermo Technical Scale (PTS value = +0.17). 1950 DA is the only known asteroid whose danger could be above the background level. The uncertainty in the probability of a collision in 2880 is due mostly to uncertainty in the Yarkovsky acceleration, which depends on the object's shape, spin state, and global distribution of optical and thermal properties. This example establishes the fundamental inseparability of asteroid physical properties and long-term prediction of their trajectories: if we take the hazard seriously, physical characterization must be given high priority.

For most NEAs, radar is the only Earth-based technique that can make images with useful spatial resolution (currently as fine as ~10 m). With adequate orientational coverage, delay-Doppler images can be used to construct geologically detailed three-dimensional models (e.g.,[5]), to define the rotation state, and to constrain the internal density distribution. The wavelengths used for NEAs at Arecibo (13 cm) and Goldstone (3.5 cm), in combination with the observer's control of the transmitted and received polarizations, make radar experiments sensitive to the surfaceís bulk density and to its roughness at scales larger than a centimeter (e.g., [6]). The fact that NEAsí circular polarization ratios (SC/OC) range from near zero to near unity means that the surfaces of these objects are extremely variegated. In many cases, NEA surfaces have more severe small-scale roughness than that seen by spacecraft that have landed on the Moon, Venus, Mars, or Eros (whose SC/OC is near the NEA average of ~ 0.3).

Radar-derived shape models of small NEAs open the door to a wide variety of theoretical investigations that are central to a geophysical understanding of these objects. With realistic models, it is possible to explore the evolution and stability of close orbits (e.g., [7]) with direct application to the design of spacecraft rendezvous and landing missions. Given information about the internal density distribution, one can use a shape model to estimate the distribution of gravitational slopes, which can constrain regolith depth and interior configuration. A shape model also allows realistic exploration [8] of the potential effectiveness of nuclear explosions in deflecting or destroying hazardous asteroids.

The most basic physical properties of an asteroid are its mass, its size and shape, its spin state, and whether it is one object or two. Radar is uniquely able to identify binary NEAs, and at this writing, has revealed six ([9] and references therein, [10]), all of which are designated Potentially Hazardous Asteroids (PHAs). Analysis of the echoes from these objects is yielding our first information about the densities of PHAs. Current detection statistics suggest that between 10% and 20% of PHAs are binary systems.

The risk of a civilization-ending impact during this century is about the same as the risk of a civilization-ending impact by a long-period comet (LPC) during this millennium. At present, the maximum possible warning time for an LPC impact is probably between a few months and a few years. Comet trajectory prediction is hampered by optical obscuration of the nucleus and by uncertainties about nongravitational forces. Radar reconnaissance of an incoming comet would be the most reliable way to estimate the size of the nucleus [11] and would be valuable for determining the likelihood of a collision.

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USING A SOLAR COLLECTOR TO DEFLECT A NEAR EARTH OBJECT. James F. Pawlowski
Human Exploration Science Office, Johnson Space Center, Houston, TX. 77058 james.f.pawlowski1@jsc.nasa.gov

Introduction: In my review of various non-nuclear techniques that might be used to deflect a NEO on a collision course with Earth, the most promising method is one that. was studied by H.J. Melosh et al * . This method uses a solar collector to focus the Sun's rays on the NEO's surface where evaporation of the surface caused by heat creates a thrust which modifies the NEO's trajectory over a period of time.

Such a technique has a huge advantage because it neither requires stabilizing the NEO nor landing on it. As the NEO rotates under the illuminated spot, fresh material is brought into the heated area so evaporation is continuous. Furthermore it does not, for the most part, depend on the composition of the NEO. It can evaporate stony or icy bodies but probably not iron NEOs. Fortunately these are rare. The steady push generated by solar evaporation minimizes the danger of disrupting the NEO in contrast to an impulse.

There are quite a few technical hurdles to overcome in maturing this technique, but none seem improbable or anymore difficult than other methods.

* Melosh, H.J., Nemchinov, I. V., Zetzer, Y. I. :1994, Hazards Due to Comets and Asteroids, pp. 1119-1127

Imaging the Interiors of Near-Earth Objects with Radio Reflection Tomography

Ali Safaeinili and Steven J. Ostro
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109-8099

Scenarios for mitigation of asteroid/comet collisions include the use of explosives to deflect or destroy the projectile (Ahrens and Harris 1995). However, as demonstrated by Asphaug *et al.* (1998), the outcome of explosive energy transfer to an asteroid or comet (via a bomb or a hypervelocity impact) is extremely sensitive to the pre-existing configuration of fractures and voids. A porous asteroid (or one with deep regolith) significantly damps shock wave propagation, sheltering distant regions from impact effects while enhancing energy deposition at the impact point. Parts of multi-component asteroids are similarly preserved, because shock waves cannot bridge inter-lobe discontinuities. Thus our ability to predict the effect of detonating a nuclear device at an asteroid or comet will rest on what we know about the object's interior.

Information about the interiors of near-Earth objects is extremely limited. Results from NEAR-Shoemaker's year-long rendezvous of Eros (Prockter *et al.* 2002, Veverka *et al.* 2000) suggest that it is somewhat consolidated, with a pervasive internal fabric that runs nearly its entire length and affects some mechanical responses such as fracture orientation. However, Eros' detailed internal arrangement of solid and porous domains is unknown, and in any case, Eros is not hazardous and is orders of magnitude more massive than any potentially hazardous asteroid. For much smaller asteroids whose shapes have been reconstructed from ground-based radar imaging (e.g., Hudson and Ostro 1995, Hudson *et al.* 2000) and for radar-detected comet nuclei, (Harmon *et al.* 1999), some interesting but non-unique constraints on density distribution have resulted.

We would like to suggest that Radio Reflection Tomographic Imaging (RRTI) (Safaeinili *et al.*) is an optimal technique for direct investigation of the interior of a small body by a spacecraft in orbit around it. The RRTI instrument’s operating frequency is low enough so that its radio signals are able to probe the target body's interior. The data obtained by RRTI is three-dimensional since it consists of wideband echoes collected on a surface around the object. This three-dimensional data set can be operated on to obtain the three-dimensional spatial spectrum of the object. The inversion of the RRTI data can yield the three-dimensional distribution of complex dielectric constant, which in turn can reveal the presence of void spaces, cracks, and variations in bulk density.

The mathematical basis of the technique is similar to that of ultrasonic reflection tomography (Kak and Slaney 1988) and seismic imaging (Mora 1987). Design of a spaceborn RRTI instrument for a small-body rendezvous can be based on the heritage from other planetary radar sounders like MARSIS (Picardi *et al.* 2001) and radar sounding experiments used to study glaciers (Gudmandsen, 1971) or contemplated for searching for a Europa ocean (Johnson *et al.* 2001). However, unlike these planetary radar sounding instruments, RRTI of NEOs would exploit the spacecraft's access to all sides of the body. Global views of the object make it possible to solve for the three-dimensional dielectric constant variations within the object down to the size of the shortest observing wavelength.

RRTI is distinctly different from radio transmission tomography techniques (e.g. the CONSERT experiment on Rosetta; Kofman *et al.* 1998) whose purpose is not imaging but rather to study material properties of radio-transparent comets. RRTI is an imaging technique that uses a co-located transmitter and receiver, and therefore does not require that the illuminating signal pass entirely through the target.

Therefore, an RRTI system can be used to image the interiors of both comets and asteroids throughout the volume penetrated by the radar echoes.

The volumetric dielectric properties of the asteroid or comet can be reconstructed using least-squares inversion (e.g., a conjugate gradient search; Safaeinili and Roberts 1995, Lin and Chew 1996) driven by the observed difference between model-predicted radio echoes and the measured radio signals. A computationally less intensive and reasonably accurate inversion is possible with the Born approximation, which ignores multiple reflection within the target and linearizes the dependence of the scattered field on dielectric variations.

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INFERRING INTERIOR STRUCTURES OF COMETS AND ASTEROIDS BY REMOTE OBSERVATIONS.

Nalin H. Samarasinha, *National Optical Astronomy Observatory, Tucson, AZ 85719, USA (nalin@noao.edu).*

Introduction: Detailed determinations of the interior structures of comets and asteroids require space missions equipped with suitable instruments. While such missions are essential for the furtherance of our knowledge on the interior structures of comets and asteroids, cost considerations alone may force such studies to be focussed on a selected set of targets. Additional useful and complementary information on the interior structures can be derived by studying the spin states of asteroids and spin states and activity of comets, primarily via groundbased studies. Structural information based on rotation depends on (a) fastest spin rates for an ensemble of asteroids (or comets) and (b) the damping timescale for non-principal axis rotators. Here, we will discuss capabilities and limitations of both these procedures for determining structural parameters. In the case of comets, activity and associated effects could provide additional useful information on the interior structure. Finally, we present a brief discussion on how activity and splitting events could affect the size distribution of cometary nuclei, and by extension, a signi£cant fraction of NEOs.

Spin Rate: None (except one at the moment; Pravec *et al.* 2002) of the asteroids larger than 200m have rotational periods smaller than 2 hrs, whereas many small NEOs (<200m) have spin rates much larger (e.g., Harris 1996, Pravec and Harris 2000, Whiteley *et al.* 2002, Paolicchi *et al.* 2002; also see Holsapple 2001). Therefore, **most** asteroids larger than 200m should be of "rubble pile" nature (for a possible exception, see Cheng 2002 and references therein) whereas the small NEOs are likely to be monoliths.

In the case of comets (excluding extinct or dormant comet candidates), none of them have rotational periods smaller than about 5.5 hrs (e.g., Meech 2002). Unfortunately, we need more data to make a robust assessment; however a lower cut-off spin rate for comets is consistent with a lower bulk density (when compared with that of asteroids). If indeed 5.5 hr corresponds to a critical spin period for comets, that would imply a bulk density near 0.4 g cm^{-3}.

Damping Timescale: Comets and Asteroids can become rotationally excited from the dynamically stable least energetic rotational state — where an object rotates around its short axis. The primary mechanisms for this excitation are (a) collisions, and/or (b) outgassing related effects (reaction torques and changes to the moment of inertia due to mass loss including that due to splitting events).

Changes in stresses and strains in the interior of a non-principal axis rotator causes the loss of mechanical energy. Therefore ultimately, in the absence of any other excitation event, the object will evolve towards the least energy rotational state. The damping timescale, t_d, for this process is given by $t_d = K \frac{\mu Q}{\rho R^2 \omega^3}$ where K is a non-dimensional scaling coef£cient, μ is the rigidity, Q is the quality factor, ρ is the density, R is the radius, and ω is the rotational angular velocity (e.g., Burns and Safronov 1973). Despite the universal agreement between the functional form of this damping timescale, there is considerable disagreement on the speci£c value of K which may vary over two orders of magnitude (e.g., Efroimsky 2001). This discrepancy is due to different model approaches to the problem and the fact that damping timescale is a strong function of the degree of excitation. When $\frac{M^2}{2E}$ is near either I_s, I_i, or I_l (where M is the rotational angular momentum, E is the rotational kinetic energy, and I_j's are moments of inertia for the small, intermediate, and long axis), the object is in a quasi-principal axis rotational state (also Samarasinha *et al.* 1999). Consequently, the loss of mechanical energy becomes a less ef£cient process near principal axis rotational states. Efroimsky (2001) calls the slowing down of the damping timescale near $\frac{M^2}{2E} = I_i$ as a "lingering effect". A detailed understanding of the dependency of damping timescale as a function of the degree of excitation is necessary for a robust assessment of structural parameters and therefore for effective utilization of the damping timescale as a probe of the interior structure.

Activity: Jewitt (1999) points out that many short period cometary nuclei should be in excited rotational states based on excitation and damping timescales. When mass loss and splitting events are taken into consideration, this argument is even stronger. However, available observational data are not consistent with this scenario.

In order to resolve this discrepancy, we suggest that it is necessary to (a) obtain rotational lightcurves with high S/N over large time baselines — in order to search for evidence of unrelated multiple periodicities (cf. Comet Encke; Belton 2000), and (b) have a better understanding of damping timescales — especially the functional dependency on the degree of excitation, $\mathcal{E}$ $(= \frac{I_s - M^2/2E}{I_s - I_l})$.

Activity Based Mechanisms for Breaking up or Splitting Comets: These include rotational splitting (e.g., Sekanina 1982), tidal splitting (e.g., Sekanina 1997), as well as activity or gas pressure caused breakups (e.g., Samarasinha 2001).

Gas pressure buildup associated with cometary activity can cause nuclei to breakup or split (e.g., comet LINEAR (C/1999 S4); Samarasinha 2001, Oort cloud comets; Levison *et al.* 2002). Samarasinha (2001) argues that a cometary nucleus containing inter-cometesimal voids and individual cometesimals but "suf£ciently blocked" void outlets could result in buildup of interior gas pressure due to super-volatiles. This was proposed as a likely mechanism for the complete catastrophic breakup of comet LINEAR (C/1999 S4).

Effects of Activity on the Size Distribution of Comets: There are two main mass loss mechanisms, namely (a) outgassing, and (b) splitting events (>1 event per comet per 100 yr; Chen and Jewitt 1994)

In order to understand the effects of activity on the size distribution of comets, we introduce a simple model in which we assume
(a) a constant active fraction through out the entire time (i.e., neglecting production of extinct/dormant cometary nuclei), and (b) a splitting rate independent of R_N.

These assumptions translate to

$$R_{N_{new}} = R_{N_{old}} - \frac{f_m t}{\rho}$$

where R_N is the nuclear radius, ρ is the bulk density, and f_m is orbitally averaged mass loss rate per unit area due to outgassing, and

$$R_{N_{new}} = R_{N_{old}}(1-f)^{1/3}$$

where f is fractional mass loss per splitting event.

We £nd that for suitable model parameters, the activity causes the size distribution of comets to peak approximately around 1 km. In other words, activity causes a lack of sub-km size comets. This is also in agreement with recent observational evidence from Meech *et al.* (2002).

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CLOSE PROXIMITY OPERATIONS AT SMALL BODIES: ORBITING, HOVERING, AND HOPPING. D.J. Scheeres, *Department of Aerospace Engineering, The University of Michigan, Ann Arbor, MI 48109-2140. E-mail: scheeres@umich.edu, Voice: 734-615-3282, Fax: 734-763-0578*.

Central to any characterization or mitigation mission to a small solar system body, such as an asteroid or comet, is a phase of close proximity operations on or about about that body for some length of time. This is an extremely challenging environment in which to operate a spacecraft or surface vehicle. Reasons for this include the *a priori* uncertainty of the physical characteristics of a small body prior to rendezvous, the large range that can be expected in these characteristics, and the strongly unstable and chaotic dynamics of vehicle motion in these force environments. To succesfully carry out close proximity operations about these bodies requires an understanding of the orbital dynamics close to them, a knowledge of the physical properties of the body and the spacecraft, and an appropriate level of technological sensing and control capability on-board the spacecraft. In the companion article to this abstract (see the proceedings of the Workshop on Scientific Requirements for the Mitigation of Hazardous Asteroids and Comets, M.J. Belton, D.K. Yeomans, and T. Morgan, Editors, Cambridge, 2003) we discuss the range of possible dynamical environments that can occur at small bodies, their implications for spacecraft control and design, and technological solutions and challenges to the problem of operating in close proximity to these small bodies.

Following is an outline of the talk that was given at the workshop, which also details what is covered in the chapter.

1. Motivation

   Mitigation and detailed characterization of asteroids and comets requires some period of close proximity operations. To support close proximity operations requires an understanding of:

   - Dynamics of natural material on and about small bodies.
   - Dynamics, navigation, and control of artificial objects on and about small bodies.

   A close coupling exists between the dynamics of natural and artificial material.

2. What's the Problem?

   - Large ranges in crucial physical parameters are possible for small bodies.
   - Each set of parameter values can have close proximity dynamics that are difficult in and of themselves.
   - These difficulties can drive spacecraft designs and mission operation concepts in very different directions.
   - We may not know some of these crucial parameters prior to rendezvous.
   - It is likely that vehicle designs and operations concepts that fit one class of small bodies will not fit another class.

3. What are the important parameters?

   Following is a list of the important small body parameters for close proximity operations, along with the ground-based observation types from which they may be estimated or inferred.

   - Size: discovery magnitude, radar.
   - Body Type/density: spectral observations.
   - Shape/gravity field/density distribution: radar, lightcurves (shape only).
   - Spin rate and spin state: radar, lightcurves.
   - Orientation of rotation angular momentum relative to orbital plane: radar, lightcurves.
   - Number of co-orbitals (i.e., binary asteroid): discovery observations, radar, lightcurves.
   - Surface/interior morphology: radar (surface only).
   - Heliocentric orbit: discovery observations.

4. What about after rendezvous?

   Following rendezvous, precision models of the body must be estimated using navigation data, which generally consists of radio metric tracking data, optical observations, and altimetry. Following are the crucial parameters needed to support close proximity operations, and the primary data they can be estimated from.

   - Mass: radiometric.
   - Gravity field: radiometric, optical, altimetry.
   - Spin state: radiometric, optical, altimetry.
   - Surface topography and roughness: optical, altimetry.
   - Surface gravity field, density distribution: gravity field plus shape.

5. What's so special about close proximity dynamics?

   Motion can be "far" from Keplerian due to perturbations from solar radiation pressure (SRP), shape (gravity), and rotation. As a result of this:

   - Trajectories can escape, impact, or migrate substantially over a few orbits.
   - The time scale of these effects are on the order of a few hours to days.
   - Surface motion must deal with these same issues.

6. What should we worry about?

   The following items are of specific concern to the implementation of close proximity operations on or about a small body.

   - Natural dynamics of disturbed regoliths:
     - Particles ejected from the surface can form a transient "atmosphere" that can linger for hours to days.
     - Re-impact of disturbed ejecta can occur anywhere over the surface at speeds up to local escape speed, $\sim$ 2 m/s for a 1 km asteroid.
     - Low velocity ejecta can have the longest "hang-times" before re-impact.
     - Non-escaping, higher-speed ejecta can migrate over the surface due to rebound.
   - Orbit Mechanics:
     - Direct orbits within 5 mean radii (for an NEA with a rotation period of $\sim$ 5 hours) will usually impact/escape from the asteroid due to gravity and rotational interactions.
     - Synchronous orbits are almost always unstable.
     - Solar radiation pressure (SRP) can strip a spacecraft out of orbit or force it to impact over a few orbits.
     - For small asteroids, interactions between gravitational effects and solar radiation pressure can rapidly destabilize motion.
     - For binary asteroids, safe orbits will generally lie outside the secondary, orbits within the secondary must contend with 3rd body and gravity field perturbations.
   - Surface motion:
     The most feasible method of locomotion appears to be hopping. Serious issues exist with this approach to travel over small bodies:
     - Thresholds for surpassing surface barriers and for launch into non-parabolic trajectories can be similar.
     - Even modest coefficients of restitution can result in long settling times, which leads to uncontrolled migration across the surface.
     - "Escape" from local surface traps may require jumps large enough to be completely unpredictable, possibly including escape!
     - Coupling between translational motion and induced rotation of the rover can occur.
     - Disturbance of surface regolith may form a transient atmosphere.

7. What can we do to counter these effects?

   Following are some known strategies for mitigating some of the adverse dynamical effects that exist at small bodies. These are by no means exhaustive, but are representative of the types of approaches that can be used. Each of these strategies have their own drawbacks, making the design of a close proximity mission a challenging exercise in system optimization.

   - Orbital mechanics techniques:
     - For larger bodies: close orbits that are retrograde to the body rotation.
       Drawbacks include:
       * Very restrictive geometry.
       * Not conducive to surface sampling.
       * Likely to be disrupted by SRP perturbations for smaller NEA's.
     - For nearly spherical, small bodies: close orbits that lie in the sun-terminator plane.
       Drawbacks include:
       * Restrictive geometry.
       * Susceptible to destabilization by gravity field coefficients.
       * For very small asteroids, may not be bound.
     - For binary asteroids: not studied to date
   - Surface motion:
     - Design surface paths that travel from regions of high potential to regions of low potential.
       * Requires construction of topographic maps with relatively unobstructed pathways identified.
       * May wish to avoid dust ponds.
       * Robust implementation will require long-term battery usage.
     - Can define maximum "jump" speeds as a function of location that ensure capture at the asteroid, and containment within a region.
     - Relatively little study of this issue to date.
   - Active control of spacecraft:
     - Two basic approaches to controlled motion exist:
       * Hovering relative to the sun-line (near-inertial).
       * Hovering relative to the rotating body.
     - These are feasible at smaller bodies where orbital techniques will fail. Require minimum levels of capability on-board:
       * Altimetry.
       * Optical or scanning laser positioning capability.
       * Precise control of small thrusters.
       * May require extended periods of operations out of sunlight.

- Inertial hovering
    * Spacecraft fixes its position relative to the body in the rotating body-sun frame, creating an artificial equilibrium point.
    * Requires closed-loop control to stabilize (which requires only minimal effort).
    * To be implemented by the Muses-C mission during the characterization phase.
    * Drawbacks:
        · Does not allow for precise measurement of mass/gravity field during observation period.
        · Limits body observations depending on spin state.
        · Becomes unstable close to the rotating body.
- Body-fixed Hovering
    * Spacecraft fixes its position relative to the body surface in the rotating body-fixed frame, creating an artificial equilibrium point.
    * Controllable with altimetry alone.
    * Precursor to landing/lift-off sampling runs.
    * Basic approach to be used by Muses-C during sampling.
    * Has been studied and simulated in some detail.
    * Drawbacks:
        · Requires periods of off-sun in general.
        · Requires accurate knowledge of gravity and topology.
        · Becomes strongly unstable at higher altitudes.
- Surface relative motion
    * Body-fixed hovering opens an alternative to moving over the surface.
    * Possible to generalize surface-relative hovering into surface-relative translations.
    * Requires a relatively complex navigation system – but not beyond current technology.

8. What are the open questions?

   This chapter covers a number of different issues. To synthesize and direct future investigations, in the following a short list of open issues are given. These are not comprehensive, but are only intended to indicate some of the current limitations in our knowledge.

   - Dynamics
       - in binary asteroid environments.
       - of surface-hopping rovers.
       - of transient atmospheres and re-impacting ejecta.
   - Stability limits of inertial-hovering.
   - Dynamics, control, and navigation of controlled surface-relative motions.

9. What do we need to know?

   Ultimately, close proximity missions are driven by the small body environment that they will encounter. This is an important point that leads to a strong emphasis on pre-launch observation campaigns for target bodies.

   In conclusion:

   - Missions to asteroids with known physical properties are simpler.
   - Missions to asteroids with unknown physical properties are:
       - more complex.
       - require additional levels of contingency.
       - cannot necessarily rely on one close proximity technology.
   - Necessary physical characteristics needed to decide close proximity approach prior to design/launch:
       - Binary or not.
       - Size/Type.
       - Spin rate/Spin state.
       - Shape.

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NEO IMPACT HAZARD: THE CANCER METAPHOR. Duncan Steel, Joule Physics Laboratory, University of Salford, Greater Manchester M5 4WT, United Kingdom; d.i.steel@salford.ac.uk

Introduction: Informing the public and the media about the NEO impact hazard has proven to be a major communication challenge. Although the fact of our planet's liability to be struck a catastrophic blow by an extraterrestrial object with devastating consequences for civilization has been known throughout the era of modern astronomy (for example Edmond Halley warned in the 1690s that comets like that bearing his name are possible Earth impactors), it has only been over the past dozen years or so that serious discussions have focused on the level of the hazard as compared to other natural and man-made disasters. This period of time also coincides with the development of technologies that make it feasible for us to search out any impending (decadal time scale) threat of impact by an asteroid or comet, and perhaps take ameliorative action if sufficient warning time is available.

The fact that, given a suitable appropriation of funding, we are now able to attempt seriously in coming years the twin aspects of NEO surveillance (initially down to 200-300 meter sizes using ground-based telescopes, and later to 50 meter sized 'Tunguskas' using space-based systems) and NEO mitigation (a more problematical area, but surely tractable: it *must* be for our continued survival), means that heightened efforts are necessary in order to communicate with the public on this matter.

Broadly speaking, there are two sides to the communication task that need emphasis, in order to aid the public in developing an understanding of the NEO impact hazard and consequently help to achieve the desired final result (i.e. an appropriate planetary defense system). The first is connected with the nature and level of the hazard: how does one juxtapose the known catastrophic consequences of an NEO impact with the rarity of their occurrence, and most especially the lack of a truly major event during historic times? (The latter situation is not only to be expected on statistical grounds, but is also a conditional result: that is, we would not be able to discuss it, had a 2 km asteroid struck the Earth 2,500 years ago, because the development of civilization would have been interrupted even if the human race survived, as would be anticipated.) The fundamental public communication problem here stems largely from the apparent fact that the average person, even with a college education, tends to have a marked lack of understanding of two areas of scientific study beginning with a 'P': physics, and probability.

The other side to the communication task requiring careful attention is almost the contrary of the above. It is a matter of instilling in the public some confidence that the NEO impact danger is a problem that is solvable; indeed solvable at a cost that is far less than the expectation of loss, so that it makes no economic sense simply to ignore it.

As a tool capable of addressing both these prongs – on the one hand the seriousness yet rarity of the hazard, on the other hand the fact that it is within our capabilities to fix it – I have developed a metaphor based on a concern that faces all humans: the possibility of developing some form of cancer. We are all aware of this disease, and will have experience of friends and relatives (and perhaps even ourselves) suffering from it. Many take steps in order to reduce the cancer risks they face, for example by avoiding tobacco smoke, or not ingesting carcinogens, or wearing sunscreen. And yet cancer can strike the most diligent risk-avoider. Nevertheless the obvious deleterious effects of cancer can be ameliorated and perhaps cured, in many cases, so long as the appropriate steps are taken. So it is with NEOs.

The Cancer Metaphor: Why facing up to hazardous asteroids and comets is like dealing with cancer:

(1) *Early identification is vital*
Most cancers need to be picked up very early in their development if they are to be treatable. So it is with NEOs. We have no time to lose in identifying any potential Earth impactor: there is no phony war with these objects.

(2) *Cancer screening (and NEO surveillance) is cheap*
The cost of screening is smaller than the cost of treatment, and much less than the cost of doing nothing.

(3) *Everyone can be involved in some way*
Self-inspection (e.g. for breast, skin or testicular cancer) is simple; but a corollary is that detailed investigations (e.g. for brain tumours) are expensive. Similarly amateur astronomers can provide vital help, although in the end the professionals will need to tackle the job.

(4) *Identification of a real problem is unlikely*
Individuals are unlikely to contract specific cancers for which screening is done, but we must aim to check everyone periodically. In the same way we need to seek out all NEOs, and keep tabs on them.

(5) *False alarms are common*
Any indicator of a potential problem necessitates careful monitoring, and causes considerable worry. But one should be pleased when the tumour proves benign. Precisely the same applies to NEOs: asteroids and comets discovered and initially flagged to be potential impactors but later shown to be sure to miss our planet represent victories on our part.

(6) *Tackling any confirmed cancer (NEO impact) is certain to be unpleasant*

No-one suggests that chemotherapy, radiotherapy or surgical intervention are fun, but they are necessary, as would be the steps employed to divert an NEO, such as the nuclear option. Nor would they be cheap: but the cost would be of no consequence, as with a serious cancer.

(7) *Just because we don't yet know the cure for cancer does not mean that we should give up looking and trying.*

Where there is life, there is hope. If we should find an NEO destined by the clockwork of the heavens to impact the Earth in the near future (within the next few decades to a century, say), and using our advanced science and technology we manage to divert it and so save ourselves, this will rank as perhaps the greatest achievement of modern-day civilisation.

(8) *Just because there are more significant problems facing the world does not mean that we should ignore this one.*

Having a bad cold or influenza does not mean that you should neglect to have the lump in your breast or the suspicious, dark skin blemish on your neck checked out.

Another viewpoint would be that if there is a substantial NEO due to strike our planetary home soon, then we face no greater problem: not terrestrial disasters, not terrorism, not wars, not disease, not global warming, not unemployment nor economic downturns. The most likely result of a proper study of the impact hazard is that it will go away, because we will find that no impact is due within the foreseeable future. But the converse is also true: what we now see as a slim chance (low probability of a large impact) may turn into a virtual certainty, which would then supplant our Earthly concerns.

(9) *Just because we don't yet know a cure for the common cold does not mean that we cannot find the solution for this disease.*

Some of the greatest dangers we face on a daily basis have quite simple solutions, like imposing speed limits to cut down road fatalities. Conceptually, planetary defense against NEO impact is a far simpler problem than, say, trying to stop major earthquakes or volcanic eruptions, or halting a hurricane in its path.

(10) *While searching for the cure for cancer we may anticipate discovering many other useful things.*

It is the very nature of scientific enquiry that discoveries are made which could not have been imagined prior to beginning the project. In the case of NEOs, it is already known that among their number are the most accessible objects in space, easier to get to than the surface of the Moon, and they contain the metals, the water/oxygen and the other materials that we will need for our future exploitation of the high frontier.

(11) *One advantage aiding the achievement of the desired outcome if cancer is diagnosed is a positive and confident outlook.*

We must be optimistic about our ability to solve this problem, else our efforts are doomed to failure before we begin. Doctors note how positive patients are more likely to make a full recovery from their illnesses, and we should habitually adopt the same attitude.

(12) *Many people survive cancer. Similarly we may confidently anticipate not only a cure for all cancers in the future, given investment in research, but also a full solution to the NEO impact hazard.*

In the past people have planted great gardens with trees that they knew would only be fully grown and appreciated in their great-grandchildren’s day. Similarly, we do things now for the future. There is most likely no large NEO due to strike the Earth within the next century, but there is certain to be a calamitous impact at some time in the future, unless we intervene. We have inherited the Giza Pyramids, the Eiffel Tower, the Golden Gate Bridge, the Taj Mahal and the Sydney Opera House, along with great works of art, music and literature. We must safeguard them, add our own contributions, and pass them on to future generations. This is only feasible if we know that some stray NEO is not going to rudely interrupt the progress of civilisation. We are able to do this. We must.

Conclusion – Avoiding Bad Stars: Finally an etymological aside. I note that ‘dis-ease’ means ‘bad ease’ and refers to a potentially fatal malady. Similarly ‘disaster’ literally means ‘bad star’ – perhaps a fatal asteroid. Planetary defense is therefore the only *disaster* mitigation of which we are capable, taking the precise original meaning of the word.

EDDY CURRENT FORCE ON METALLIC ASTEROIDS. Duncan Steel, Joule Physics Laboratory, University of Salford, Salford M5 4WT, England, UK; D.I.Steel@Salford.ac.uk

Introduction: In order to make accurate predictions of the future orbital evolution of Earth-approaching asteroids it is necessary to take into account non-gravitational forces. As has recently been demonstrated [1], radiation forces (in particular the Yarkovsky force) depending on the surface properties of a specific relatively large asteroid will affect predictions of whether it will impact the Earth some centuries hence. Since the surface area varies as r^2 (r being the body's radius), the perturbation/acceleration varies as $1/r$, and so smaller asteroids may be affected on shorter time scales.

Astronomers studying meteoroids and interplanetary dust have studied such radiative perturbations for some decades, and also considered the Lorentz and Faraday forces due to interactions with the interplanetary magnetic field. For objects of asteroidal size the perturbations produced are much smaller than the radiation-induced effects, as shown below.

Another class of force due to magnetic fields is the eddy current (or Foucault current) force that would act on a metallic asteroid. This depends on the (square of the) gradient of the interplanetary magnetic field, which may be substantial only at sector boundaries or in a turbulent magnetic field. It may thus act only episodically. This force is always dissipative, slowing down the object in question.

Another location where an asteroid experiences a magnetic field gradient is in passing close by a planet. In particular, in the present context it is noteworthy that objects due to hit the Earth in the not-too-distant future may be expected, in many cases, to make numerous close passages past our planet before the impact occurs. Any transit through the terrestrial magnetosphere will result in the imposition of a significant eddy current force.

The important point about the eddy current force is that it varies as r^3 and so the perturbation produced will be size/mass independent. On the other hand, voids within an asteroid will inhibit the eddy currents and so limit the force imposed. Estimates of the eddy current force outlined here indicate that generally it is rather smaller than the radiative forces. Nevertheless, these results do show that the internal structure of a metallic asteroid may be significant with regard to specifying its dynamical evolution.

Radiation Pressure Benchmark: Although the Yarkovsky-Radzievskii force [2] may be of greater magnitude, it is complicated to model and so for simplicity we will adopt as a benchmark here the radiation pressure force imposed on a body by solar photons. Similarly the Poynting-Robertson force is neglected, as this will be small for a large (asteroidal) object.

The solar photons absorbed by the asteroid in question, which is assumed to be a homogeneous sphere, will impose an outward force. Meteoroid researchers have for many years been habituated to employing an additional term ($1-\beta$) in Newton's Law of Gravity, where β is a factor that depends on the size and scattering properties of the meteoroid in question. For radius r = 0.5 mm, $\beta \approx 0.0004$ for a nominal meteoroid (stony) density. Because an object's mass increases as r^3 whereas its cross-sectional area increases only as r^2, the importance of the radiation pressure force is much lower for large bodies (i.e. β has much lower values).

At 1 AU the pressure applied by sunlight is ~4.5×10^{-6} N m^{-2} if all photons are simply absorbed. (This corresponds to an unreal albedo of zero, but on the other hand any scattered photons will impose a larger force so that a highly reflective body would suffer a larger radiation pressure force.)

For an asteroid with diameter D = 1 km the total radiation pressure force applied is therefore approximately 3.5 N at 1 AU. Momentum transfer by absorbed solar wind particles will enhance this by 20-30 percent, so that a characteristic outward force on the asteroid is of order 5 N. This is the benchmark against we will measure the electromagnetic forces considered below.

Lorentz Force: The Lorentz force (produced by surface charging so as to attain a potential of a few kilovolts) is given by:

$$F_L = Q\,(\underline{E} + \underline{v} \times \underline{B})$$

where Q is the electric charge on the body in question, $\underline{v}$ is its velocity, and $\underline{E}$ and $\underline{B}$ are respectively the electric and magnetic fields through which it is passing. Here we assume that $E = 0$, and v = 30 km s^{-1}, and $B \approx 1\times10^{-8}$ T is a typical interplanetary field strength. The charge Q on a spherical asteroid photoionized to $V \approx 2000$ volts is $Q \approx 1\times10^{-4}$ coulombs. If $\underline{v}$ and $\underline{B}$ are orthogonal then $F_L \approx 3\times10^{-8}$ N.

This is much less than the radiation pressure benchmark. Nearer the Sun, v, B and Q are larger and so F_L might be enhanced by a couple of orders of magnitude, but it will still be small.

Magnetic (Faraday) Force: The magnetic force (produced by a current flowing through an asteroid, assumed to be metallic, without voids, with the conductivity of the loop limited by the pick-up rate of solar wind electrons/ions) is given by:

$$F_M = B\,i\,L$$

where i is the electric current flowing through the asteroid and L is a characteristic length, taken here to be the diameter D. We again employ $B \approx 10^{-8}$ T.

The current i flowing through the asteroid is limited by its charge pick-up from the solar wind. The important velocity here is not that of the asteroid relative to the Sun, but that of the solar wind relative to the asteroid. At 1 AU this is typically 500 km s^{-1} although storm speeds of order 1000 km s^{-1} do occur.

The solar wind spatial density at 1 AU is typically of order 5–10 particles cm^{-3}, but often reaches ten times that and may be higher still following a coronal mass ejection. Here we employ a value of 100 cm^{-3} or 10^8 m^{-3}.

The electron pick-up rate will therefore be of order $\pi r^2 \times 5 \times 10^5 \times 10^8 \approx 4 \times 10^{19}$ electrons per second and so the current would be $i \approx 6.3$ amps. The magnetic force would therefore be:

$$F_M = B\, i\, D = 10^{-8} \times 6.3 \times 10^3 \approx 10^{-4}\ \mathrm{N}.$$

This is some orders of magnitude smaller than the radiation pressure force, although again the value would be elevated in the innermost solar system.

Eddy (Foucault) Current Force: The eddy current force is given by:

$$F_E = (2\pi/15)\, \sigma\, v\, (\nabla B)^2\, r^5$$

where σ is the conductivity of the body, and ∇B is the gradient of the magnetic field through which it is passing (e.g. see [3]). We want to use this to make an estimate of the eddy current force experienced by the asteroid.

For soft iron $\sigma \approx 1 \times 10^7$ siemens per metre, and we will assume that the asteroid is entirely metallic with no voids or rocky inclusions that would inhibit the free flow of the eddy currents (cf. engineering techniques used to inhibit eddy current power losses in transformers and other electrical equipment).

The magnetic field in question will be assumed to be fixed relative to the Sun, so that the velocity to use is v = 30 km s^{-1}. Now let the asteroid pass through an interplanetary field sector boundary where the magnetic flux density changes by 10^{-7} tesla over a short distance scale of 10^7 metres, so that $\nabla B = 10^{-14}$ T m^{-1} (real gradients will likely be rather less than this). Thus: $F_E = (2\pi/15) \times 10^7 \times 3 \times 10^4 \times (10^{-14})^2 \times (500)^5 \approx 4 \times 10^{-4}$ N. This is again much smaller than the radiation pressure benchmark.

Eddy Current Force Near Earth: Another situation in which the eddy current force experienced by an asteroid may be substantial, and higher than the above, is when it makes a close passage by a planet possessing a magnetic field. Of course the planet we are interested in here is the Earth, and we note that many asteroids (especially resonant returners) will make multiple passes close by our planet before any eventual impact.

What do we mean by a 'close passage' in this context? The magnetic field cavity centred on the Earth stretches out for about 15 terrestrial radii to the side, the bowshock is about 13 radii in the sunward direction, and the magnetotail stretches about a thousand terrestrial radii in the anti-solar direction. Thus we might anticipate that an asteroid could make some hundreds of transits through the magnetosphere prior to an impact.

The magnetic field at the surface of the Earth is about 5×10^{-5} T and this falls to around 10^{-8} T in interplanetary space. Fifteen terrestrial radii is about 10^5 km or 10^8 m. The gradient averaged from the surface to out beyond the magnetopause is therefore of order 5×10^{-13} T m^{-1}. Inserting this in the equation above, with all other parameters as before, one derives $F_E \approx 1$ N.

Therefore it appears feasible that the eddy current force might be of significance with regard to predicting future impacts, although the above has been only a very crude first-look at the problem.

An important point to note here is that the equation for F_E indicates it to vary as r^5. This might be taken to imply that the acceleration suffered by any body subject to eddy currents increases as r^2, which would be remarkable. In fact the extent of the gradient ∇B matches the particle size, and so F_E varies as r^3. Thus the acceleration is size-independent.

Force on a Magnetized Asteroid: There is another form of interaction that may occur between an asteroid and the interplanetary or terrestrial magnetic field. This is when the asteroid possesses a non-zero dipole moment (i.e. it is permanently magnetized itself, perhaps a relict from the time when it was part of a much larger planetesimal). This will be discussed in a future paper.

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NEA DEFLECTION: SOMETIMES RESONANT RETURNS ARE OF NOT MUCH HELP. G.B. Valsecchi, A. Carusi, *IASF-CNR, Roma, Italy, and SCN, ESA/ESRIN, Frascati, Italy (giovanni@rm.iasf.cnr.it).*

A key quantity that must be known before attempting to deflect a Near-Earth Asteroid (NEA) that is going to fall on the Earth is the Δv needed to prevent the collision.

Ahrens and Harris (1992, 1994) give two approximate expressions for Δv; for a deflection carried out shortly before impact (i.e., for $\Delta t < P$, where Δt is the time interval between deflection and impact, while P is the orbital period of the NEA) they estimate:

$$\Delta v = \frac{75\ m/s}{\Delta t\ d},$$

while for $\Delta t > P$ they estimate:

$$\Delta v = \frac{0.07\ m/s}{\Delta t\ yr}.$$

A more precise expression, based on Öpik's theory of close encounters (Öpik 1976; Carusi et al. 1990; Valsecchi et al. 2001), is given by Carusi et al. (2002):

$$\Delta v = \frac{b_\oplus \sqrt{r}}{(3U \sin\theta \Delta t + 2b_\oplus)\sqrt{a(2a-r)}},$$

with

$$\begin{aligned} b_\oplus &= \sqrt{r_\oplus^2 + 2cr_\oplus} \\ c &= \frac{m_\oplus}{U^2} \\ U &= \sqrt{3 - \frac{1}{a} - 2\sqrt{a(1-e^2)}\cos i} \\ \theta &= \arccos\frac{1 - U^2 - 1/a}{2U}, \end{aligned}$$

and where r is the heliocentric distance at which the deflection takes place, $m_\oplus$, $r_\oplus$, are the mass and radius of the Earth, and a, e, i are the semimajor axis, eccentricity and inclination of the NEA orbit; the units adopted for this expression are those standard in Öpik's theory, so that the unit of mass is the mass of the Sun, that of length is the radius of the orbit of the Earth, and that of time is such that the heliocentric orbit of the Earth has period 2π.

However, if the potential impactor has a close encounter with our planet before the one in which the collision is bound to happen, Δv can be significantly lower, as shown by Carusi et al. (2002) in the hypothetical case of the 2040 collision of (35396) 1997 XF_{11}.

This collision, in fact, would be preceded by an Earth encounter in 2028 putting the asteroid in a resonant orbit. The computations by Carusi et al. (2002) show that for a deflection taking place a short time *before* 2028, Δv would be about two orders of magnitude smaller than the one needed for a deflection taking place a short time *after* 2028.

Basically, the amount of Δv saving is related to the different mean motion perturbations imparted by the 2028 Earth encounter to two Virtual Asteroids (VAs; i.e., fictitious particles with orbits similar to that of the real asteroid) on nearby trajectories; the difference in mean motion leads to along-track separation and this, in turn, leads to different b-plane coordinates in 2040.

The b-plane, or target plane, is the plane perpendicular to the unpertubed geocentric velocity vector $\vec{U}$ of the NEA; it contains $\vec{b}$, the geocentric position vector of the NEA at closest approach along the unperturbed orbit.

The use of the b-plane leads to relatively simple analytic expressions relating the pre-encounter orbital elements of the NEA with the post-encounter ones. In particular, if the ξ-ζ reference frame of Greenberg et al. (1988) is established on the b-plane, it is easy to see that, if the NEA encounters the Earth at a distance corresponding to the Minimum Orbital Intersection Distance (MOID), the ζ-component of its $\vec{b}$-vector is 0, while if the NEA is early or late with respect to the Earth, the ζ-component varies accordingly, while the ξ-component remains unchanged.

Using this set-up, and assuming an unperturbed keplerian motion between successive Earth encounters, Valsecchi et al. (2001) obtained the following analytic expression for the derivatives of the b-plane coordinates at the *second* encounter ξ'', ζ'', with respect to those at the *first* encounter ξ, ζ:

$$\begin{bmatrix} \frac{\partial\xi''}{\partial\xi} & \frac{\partial\xi''}{\partial\zeta} \\ \frac{\partial\zeta''}{\partial\xi} & \frac{\partial\zeta''}{\partial\zeta} \end{bmatrix} \approx \begin{bmatrix} \frac{\partial\xi'}{\partial\xi} & \frac{\partial\xi'}{\partial\zeta} \\ \frac{\partial\zeta'}{\partial\xi} - \frac{4hsc\xi\zeta\sin\theta}{b^4} & \frac{\partial\zeta'}{\partial\zeta} + \frac{2hsc(\xi^2-\zeta^2)\sin\theta}{b^4} \end{bmatrix} \quad (1)$$

where h is the number of revolutions of the NEA about the Sun between the first and the second encounter (an integer number in case of a resonant return), $b^2 = \xi^2 + \zeta^2$, ξ', ζ' are the coordinates on the *post-first-encounter* b-plane (perpendicular to the post-encounter geocentric velocity vector $\vec{U'}$ of the NEA), and

$$s = \frac{2\pi a'^{5/2}[U'\cos^2\theta' + \cos\theta'(1-U'^2) - 3U']}{\sin\theta'}, \quad (2)$$

with

$$a' = \frac{1}{1 - U'^2 - 2U'\cos\theta'},$$

so that s is in fact a function of only U' and θ'. Note that $U' = U$ if the orbit of the Earth is circular, and that the difference between U and U' is negligible even for the current eccentricity of the orbit of the Earth.

In the rather common case in which the first encounter is not too close, i.e. when $c^2 << \xi^2 + \zeta^2$, the derivatives $\partial(\xi', \zeta')/\partial(\xi, \zeta)$ have the following form:

$$\begin{bmatrix} \frac{\partial\xi'}{\partial\xi} & \frac{\partial\xi'}{\partial\zeta} \\ \frac{\partial\zeta'}{\partial\xi} & \frac{\partial\zeta'}{\partial\zeta} \end{bmatrix} \approx \begin{bmatrix} 1 + \mathcal{O}(c/b) & \mathcal{O}(c/b) \\ \mathcal{O}(1) & 1 + \mathcal{O}(c/b) \end{bmatrix}. \quad (3)$$

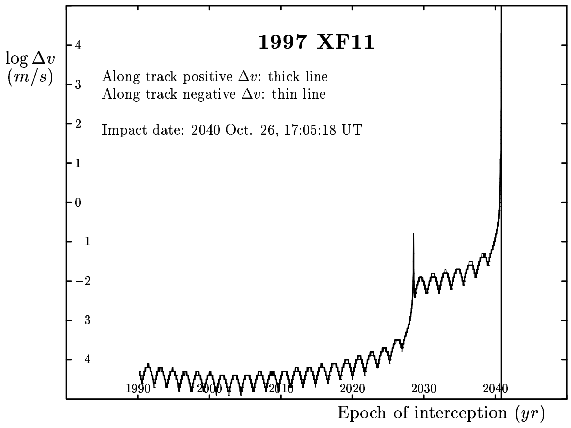

Figure 1: The amount of Δv necessary to deflect (35396) 1997 XF_{11} by 1 Earth radius as a function of the time at which the deflection takes place. The thick line is for Δv applied in the same direction as the motion of the asteroid, the thin one for Δv in the opposite direction; the two lines are almost indistinguishable because the computations have been done starting from a reference trajectory impacting the Earth almost exactly at the centre.

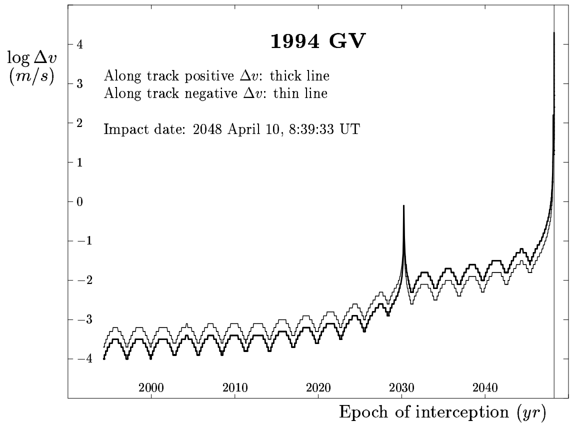

Figure 2: The amount of Δv necessary to deflect 1994 GV by 1 Earth radius as a function of the time at which the deflection takes place. The thick line is for Δv applied in the same direction as the motion of the asteroid, the thin one for Δv in the opposite direction; the two lines are rather well separated in this case because the computations have been done starting from a reference trajectory impacting the Earth far from the centre.

Equations (1) and (3) tell us that the separation between nearby VAs manifests itself on the b-plane of the second encounter mostly as an increase of the separation in ζ''; the latter grows linearly with the number of revolutions of the VAs between the two encounters (i.e., grows linearly with time). Valsecchi et al. (2001) show how the size of impact keyholes is, in fact, inversely proportional to the increase of separation between nearby VAs between the two encounters.

The rate at which this separation takes place is controlled by s, given by (2), and it is worthwhile to have a closer look at this quantity. One notices that:

- its sign is determined by the sign of the term within the square brackets (since $0 < \theta' < \pi$);
- its absolute value can be larger than 1;
- unless the first encounter of the resonant pair is very close ($c^2 \approx \xi^2 + \zeta^2$, or even $c^2 >> \xi^2 + \zeta^2$), θ' differs from θ, and thus a' differs from a, by quantities that are $\mathcal{O}(c/b)$.

The latter can be deduced from the formulae given by Valsecchi et al. (2001) for the case $c^2 << \xi^2 + \zeta^2$:

$$\begin{aligned} \theta' &\approx \arccos\left(\cos\theta + \frac{2c\zeta}{b^2}\sin\theta\right) \\ &\approx \arcsin\left(\sin\theta - \frac{2c\zeta}{b^2}\cos\theta\right) \\ a' &\approx a\left(1 + \frac{4aUc\zeta\sin\theta}{b^2}\right). \end{aligned}$$

As a consequence, in the case of a resonant pair of close encounters in which the first one is not very close, the value of s computed using the pre-first-encounter values θ and a will not differ much from the value of s computed using the post-first-encounter values θ' and a'. This means that, in practice, we can use even the *current* values of θ and a to get a quick idea of the rate of increase of the separation between nearby VAs between encounters for each of the known NEAs.

Let us now discuss, in the light of the above considerations, the case of the 2040 Virtual Impactor (VI; i.e. a VA that eventually collides with the Earth) of the Apollo asteroid (35396) 1997 XF_{11}. The orbit of this NEA is currently characterized by $a = 1.442$ AU, $e = 0.484$, $i = 4^\circ\!.1$, so that $U = 0.459$, $\theta = 84^\circ\!.0$, and $s = -20.3$.

Figure 1 shows, in the same style as in Carusi et al. (2002), the Δv necessary to avoid the collision in 2040 as function of the time at which the deflection maneuver is made. As the Figure shows, the difference between a post-2028 deflection and a pre-2028 one is that the latter requires a Δv almost two orders of magnitude smaller.

Quantitatively, this large Δv saving can be explained with the arguments discussed before; intuitively, one can simply think that, while after 2028 the Δv imparted must be sufficient to displace a NEA by $b_\oplus$ (1.3 times larger than $r_\oplus$ in this case), before 2028 the Δv must only be sufficient to deviate the NEA outside the 2040 impact keyhole present in the 2028 b-plane, a much easier task, given that the keyhole in question is quite small. The rest of the work, so to speak, is made for us by the mean motion difference, with respect to the mean motion of the VI, induced by the perturbation of the Earth at the 2028 close encounter.

However, resonant returns are not always so kind to us. The discussion about the divergence of nearby trajectories has

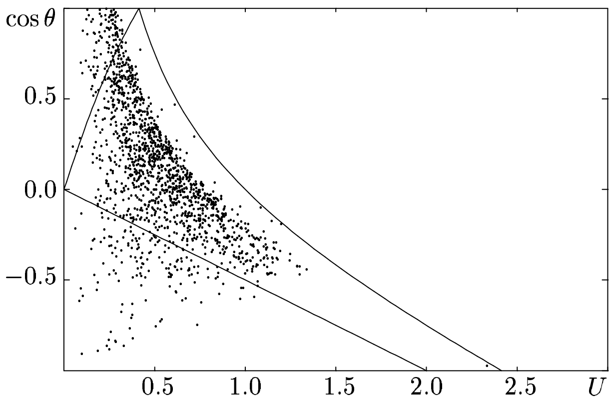

Figure 3: All currently known NEAs plotted in a U-cos θ diagram. The curved line going from $(\sqrt{2}-1, 1)$ to $(\sqrt{2}+1, -1)$ represents parabolic orbits, the straight segment from $(0, 0)$ to $(2, -1)$ the orbits with $a = 1$ AU, and the remaining line, joining the previous two, represents the condition $s = 0$.

taught us that we can expect cases in which s is small, much smaller than in the case of (35396) 1997 XF_{11}. In these cases we can *a priory* expect that a significantly reduced Δv saving would be obtained with a pre-first-encounter deflection of a NEA impacting at a resonant return.

In order to find such a case in the population of VIs of known NEAs, we examined the risk pages of both NEODyS (`http://newton.dm.unipi.it/neodys`) and Sentry (`http://neo.jpl.nasa.gov/risk`), looking for objects with low values of $|s|$, and found the Apollo asteroid 1994 GV, a very small ($H \approx 27$) object that has, among others, a VI that, after an encounter with the Earth in 2031, hits the Earth at a resonant return in 2048. Its orbit is currently characterized by $a = 2.013$ AU, $e = 0.520$, $i = 0\overset{\circ}{.}5$, giving $U = 0.282$, $\theta = 41\overset{\circ}{.}3$, and $s = 0.2$.

Figure 2 shows the results of a preliminary computation concerning 1994 GV. As expected on the basis of the small value of $|s|$, the Δv saving obtained with a pre-2031 deflection of the 2048 VI associated with 1994 GV is more than an order of magnitude smaller than the Δv saving obtained with a pre-2028 deflection of the 2040 VI associated with (35396) 1997 XF_{11}.

We have seen that, for impacts at resonant returns, there can be a substantial Δv saving if the deflection maneuver is done before the first encounter of the resonant pair.

However, the amount of the Δv saving depends on the value of s, a quantity whose approximate value can be computed from the current values of the orbital elements of the NEA under consideration. If $|s|$ is very small, the Δv saving will be small, and we have shown an example of such a case.

A quick survey of the values of s in the population of known NEAs shows that s can vary over a large range: the first quartile of the distribution is at $s \approx -51$, the median at $s \approx -24$, and the third quartile at $s \approx -9.3$. Moreover, 10% of the objects have $s > 67$, and 10% have $s < -240$. To put these numbers in perspective, let us recall that, for (35396) 1997 XF_{11}, with $|s| \approx 20$, a Δv saving of about two orders of magnitude is obtained with $\Delta t = 12$ yrs between the two encounters.

Thus, we conclude that, in the computation of the Δv saving for a pre-first-encounter maneuver for a NEA impacting at the second encounter of a resonant pair, the range of possible savings can be quite large, and depends not only on the time between the two encounters, but also on the orbital elements of the NEA in question.

In particular, the condition $s = 0$, highlighting the objects with the lowest Δv savings, is shown in a U-cos θ diagram in Fig. 3.

As a concluding remark, we note that the analytical arguments described in this paper would apply, with slight modifications, also to the case of a non-resonant return (Milani et al. 1999).

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SEISMIC INVESTIGATIONS OF ASTEROID AND COMET INTERIORS. J. D. Walker and W. F. Huebner, Southwest Research Institute, P. O. Drawer 28510, San Antonio, TX 78228-0510, USA. jwalker@swri.edu, whuebner@swri.edu.

Techniques to mitigate collisions of asteroids and comets with Earth require detailed knowledge of geophysical and geological properties of the objects. In particular, we must gather data on mass and mass distribution, moments of inertia, material strengths, internal structure, and relationship of global properties to surface properties of these objects. Global material strengths and structure are best determined from artificially activated seismology experiments and from multifrequency radio tomography. Other important properties of NEOs include the shape and the spin state. These can usually be measured by more conventional means, such as radar and light curves.

Both, radio tomography and artificially activated seismology are nondestructive means of obtaining global properties of asteroids and comets while most other means provide only local properties to a limited depth. Radio tomography and seismology have advantages and disadvantages that lead to complementary investigations of comets and porous carbonaceous asteroids on one hand and stony and metallic asteroids on the other hand. Advantages and disadvantages depend on requirements of orbiters, landers, radio frequencies, position of landed instruments, timing of seismic activations, intensities of wave propagations, sensitivities of instruments, etc. While radio tomography primarily reveals internal structures, such as fissures, discontinuities, etc., seismology can also give information about physical strengths of the materials. We discuss many of these issues, but concentrate primarily on seismology. Radio tomography is discussed in a separate papers by Kofman et al. and Safaeinili et al.

Quantitative information about the internal composition and structure of an asteroid or comet can be obtained through active seismology. Active seismology requires a source of the seismic disturbance and detectors (geophones or seismometers) to measure the sound waves produced in the asteroid or comet body. There are two approaches to producing seismic waves: Explosive charges and impactors. The active seismology program conducted on the Apollo 14, 16, and 17 flights used both. On each of the flights, the astronauts carried explosives, either to be launched in a grenade launcher or to be placed by hand as seismic source. On two of the flights, a hand-held thumper consisting of exploding bridge wires was also used as a seismic source. These experiments allowed a partial determination of the structure of the lunar surface near the landing site. In addition, information about the Moon's structure was gleaned from the seismic traces produced by the impact of the Lunar Modules (LMs) and Saturn IV B upper stGE ROCKET BODIES (SIVBs). Some of these results will be reviewed.

Next, given a size of an asteroid or comet and some assumptions about composition, we discuss the requirements for explosive charge size or impactor momentum in order to obtain signals that can be measured by various seismometers. The size of the charge ties into the coupling between the explosive and the surface material of the asteroid or comet. We discuss experiments we performed using well characterized materials to examine the coupling of small explosive charges in relation to depth into the surface of the target material. Large increases in efficiency result. The corresponding impulse loadings from impacts will be discussed, including what size impactors and impact velocities lead to similar seismic signals. Information about the required loading on the surface is then available as input for mission design, aa well as determining seismometer sensitivity requirements.

MILITARY PERSPECTIVES ON THE NEAR-EARTH OBJECT (NEO) THREAT. S.P. Worden, United States Space Command, Peterson Air Force Base, CO 80914, simon.worden@peterson.af.mil

Introduction: Interest in the threat caused by natural objects ("Near-Earth Objects" or NEOs) impacting the earth or its atmosphere is growing. High-level commissions have met to consider the problem in such places as the United Kingdom. In the United States, NASA has devoted a few million dollars per year to studying the phenomenon. But no concrete plan exists to address the overall NEO problem.

The U.S. Department of Defense (DoD) has not perceived the NEO issue as pressing. However, DoD is assisting NASA in studying the problem. It has been DoD-developed technology, particularly in the space surveillance area, which has obtained the bulk of data we currently have on NEOs.

I believe there is both a pressing need and a significant opportunity to address the NEO question. New technologies such as wide area space surveillance and microsatellite space missions give us unprecedented tools to study and, if appropriate mitigate NEO threats. Moreover, with growing cooperation between the various space agencies of the U.S. Government, including the national security sector I believe a coherent NEO approach can emerge. This can form the basis of an international program on this important problem.

The Threat: Two and a half months ago, Pakistan and India were at full alert and poised for a large-scale war, which both sides appeared ready to escalate into nuclear war. The situation has defused–for now. Most of the world knew about this situation and watched and worried. But few know of an event over the Mediterranean on June 6th of this year that could have had a serious bearing on that outcome. U.S. early warning satellites detected a flash that indicated an energy release comparable to the Hiroshima burst. We see about 30 such bursts per year, but this one was one of the largest we have ever seen. The event was caused by the impact of a small asteroid, probably about 5-10 meters in diameter, on the earth's atmosphere. Had you been situated on a vessel directly underneath, the intensely bright flash would have been followed by a shock wave that would have rattled the entire ship, and possibly caused minor damage.

The event of this June received little or no notice as far as we can tell. However, if it had occurred at the same latitude just a few hours earlier, the result on human affairs might have been much worse. Imagine that the bright flash accompanied by a damaging shock wave had occurred over India or Pakistan. To our knowledge, neither of those nations have the sophisticated sensors that can determine the difference between a natural NEO impact and a nuclear detonation. The resulting panic in the nuclear-armed and hair-triggered opposing forces could have been the spark that ignited a nuclear horror we have avoided for over a half century.

I've just relayed one aspect of NEOs that should worry us all. As more and more nations acquire nuclear weapons–nations without the sophisticated controls and capabilities built up by the United States over the 40 years of Cold War–we should ensure the 30-odd yearly impacts on the upper atmosphere are well understood by all to be just what they are.

A few years ago those of us charged with protecting this Nation's vital space systems, such as the Global Positioning System, became aware of another aspect of the NEO problem. This was the Leonid meteor storm. This particular storm occurs every 33 years. It is caused by the debris from a different type of NEO–a comet. When the earth passes through the path of a comet, it can encounter the dust thrown off by that comet through its progressive passes by the sun. This dust is visible on the earth as a spectacular meteor storm. But our satellites in space can experience the storm as a series of intensely damaging micrometeorite strikes. We know about many of these storms and we have figured out their parent comet sources. But there are some storms arising from comets that are too dim for us to see that can produce "surprise" events. One of these meteor storms has the potential of knocking out some or even most of our earth-orbiting systems. If just one random satellite failure in a pager communications satellite a few years ago seriously disrupted our lives, imagine what losing dozens of satellites could do.

Most people know of the Tunguska NEO strike in Siberia in 1908. An object probably less than 100 meters in diameter struck Siberia, releasing equivalent energy of up to 10 megatons. Many experts believe there were two other smaller events later in the century—one in Central Asia in the 1940s and one in the Amazon in the 1930s. In 1996, our satellite sensors detected a burst over Greenland of approximately 100 kiloton yield. Had any of these struck over a populated area, thousands and perhaps hundreds of thousands might have perished. Experts now tell us that an even worse catastrophe than a land impact of a Tunguska-size event would be an ocean impact near a heavily populated shore. The resulting tidal wave could inundate shorelines for hundreds of miles and potentially kill millions. There are hundreds of thousands of objects the size of the Tunguska NEO that come near the earth. We know the orbits of just a few.

Finally, just about everyone knows of the "dinosaur killer" asteroids. These are objects, a few kilometers across, that strike on time scales of tens of millions of years. While the prospect of such strikes grabs people's attention and make great catastrophe movies, too much focus on these events has, in my opinion, been counterproductive. Most leaders in the United States or elsewhere believe there are more pressing problems than something that may only happen every 50-100 million years. I advocate we focus our energies on the smaller, more immediate threats. This is not to say we do not worry about the large threats. However, I'm reasonably confidant we will find almost all large objects within a decade or less. If we find any that seem to be on a near-term collision course–which I believe unlikely–we can deal with the problem then.

What Should We Do?: First and foremost, when an object strikes the earth, we must know exactly what it is and where it hit. Fortunately, our early warning satellites already do a good job of this task. Our next generation system, the Space-Based Infrared System, will be even better. The primary difficulty is that this data is also used for vital early warning purposes and its detailed performance is classified. However, in recent years, the U.S. DoD has been working to provide extracts of this data to nations potentially under missile attack with cooperative programs known as "Shared Early Warning." Some data about asteroid strikes have also been released to the scientific community. Unfortunately, it takes several weeks for this data to be released. I believe we should work to assess and release this data as soon as possible to all interested parties, while ensuring sensitive performance data is safeguarded.

We have studied what a NEO warning center might look like. I believe adding a modest number of people, probably less than 10, to current early warning centers and supporting staffs within Cheyenne Mountain could form the basis of a Natural Impact Warning Clearinghouse.

Perhaps the most urgent mid-term task has already begun. This is the systematic observation and cataloging of nearly all potentially threatening NEOs. We are probably about halfway through cataloging "large" NEOs (greater than a kilometer in diameter). It is interesting to note the most effective sensor has been the MIT Lincoln Lab LINEAR facility in New Mexico, which is a test bed for the next generation of military ground-based space surveillance sensors. But this ground-based system, however effective, can only address the "large," highly unlikely threats. We find out every few weeks about "modest" asteroids a few hundred meters in diameter. Most sail by the earth unnoticed until they have passed. In recent months, the object 2002MN had just this sort of near miss–passing only a few tens of thousands of kilometers from the earth. Ground-based systems such as LINEAR are unable to detect one of the most potentially damaging classes of objects, such as comets that come at us from the direction of the sun. New space-surveillance systems capable of scanning the entire sky every few days are what is needed.

New technologies for space-based and ground-based surveys of the entire space near the earth are available. These technologies could enable us to completely catalog and warn of objects as small as the Tunguska meteor (less than 100 meters in diameter). The LINEAR system is limited primarily by the size of its main optics–about one meter in diameter. By building a set of three-meter diameter telescopes equipped with new large-format Charged Coupled Devices, the entire sky could be scanned every few weeks and the follow-up observations necessary to accurately define orbits, particularly for small objects, could be done.

The most promising systems for wide-area survey–particularly to observe close to the sun to see objects coming up from that direction–are space-based surveillance systems. Today the only space-based space surveillance system is the DoD's Midcourse Space Experiment (MSX) satellite. This was a late 1990s missile defense test satellite, and most of its sensors have now failed. However one small package weighing about 20 kg and called the Space-Based Visible sensor is able to search and track satellites in geosynchronous orbit (GEO) using visible light. This has been a phenomenally successful mission, having lowered the number of "lost" objects in GEO orbit by over a factor of two. MSX is not used for imaging asteroids, but a similar sensor could be. The Canadian Space Agency, in concert with the Canadian Department of National Defense, is considering a "microsatellite" experiment with the entire satellite and payload weighing just 60 kg. This Near-Earth Surveillance System would track satellites in GEO orbit, as MSX does today. However, it would also be able to search the critical region near the sun for NEOs that would be missed by conventional surveys.

The U.S. DoD is planning a constellation of somewhat larger satellites to perform our basic satellite-tracking mission. Today our ground-based radars and telescopes, and even MSX, only track objects that we already know about. These systems are not true outer-space search instruments as the LINEAR system is. However, the future military space surveillance system would be able to search the entire sky. As an almost "free" by-product, it could also perform the NEO search mission. Larger aperture ground-based systems could then be used to follow up to get accurate orbits for the NEOs discovered by the space-based search satellites. Again, I believe there is considerable synergy between national security requirements related to man-made satellites and global security requirements related to NEO impacts.

Regardless of how well we know NEO orbits and can predict their impacts, the fact remains that today, we have insufficient information to contemplate mitigating an impact. We do not know the internal structure of these objects. Indeed, we have reason to believe that many, if not most, are more in the nature of "rubble piles" than coherent objects. This structure suggests that any effort to "push" or divert a NEO might simply fragment it, which could potentially turn a single dangerous asteroid into hundreds of objects that could damage a much larger area.

What is needed are in situ measurements across the many classes of NEOs, including asteroids and comets. This is particularly important in the case of small (100 meter) class objects of the type we would most likely be called upon to divert. Until recently, missions to gather these data would have taken up to a decade to develop and launch and cost hundreds of millions of dollars. However, the situation looks much better with the emergence of so-called "microsatellites," which weigh between 50-200 kg and can be launched as almost "free" auxiliary payloads on large commercial and other flights to GEO orbit. These missions can be prepared in one to two years for about $5-10M, and launched for a few million dollars as an auxiliary payload. I believe such auxiliary accommodation is a standard feature on the European Ariane launches, and could be considered here in the United States on our new Evolved Expendable Launch Vehicles.

With a capable microsatellite with several kilometers per second "delta-V" (maneuver capacity) launched into a GEO transfer orbit (the standard initial launch orbit for placing systems into GEO), the satellite could easily reach some NEOs and perform in situ research. This could include sample return, direct impact to determine the internal structure and the potential to move a small object. Indeed, NASA is planning several small satellite missions. The key point here, however, is that with missions costing $10M each, we can sample many types of NEOs in the next decade or so to gain a full understanding of the type of objects we face.

There is an interesting concept to consider. If we can find the right small object in the right orbit, we might be able to nudge it into an orbit "captured" by the earth. This would make a NEO a second natural satellite of earth. Indeed, there is at least one NEO that is close to being trapped by the Earth now, 2002 AA_{29}. If such an object were more permanently in earth orbit, it could be more closely studied and might form the basis for long-term commercial exploitation of space. Moreover, a very interesting manned space flight mission after the Space Station could be to an asteroid; maybe even one we put into earth's gravity sphere.

One important aspect of NEO mitigation is often overlooked. Most experts prefer to focus on the glamorous "mitigation" technologies–diverting or destroying objects. In fact, as the U.S. military knows well the harder part is what we call "command and control." Who will determine if a threat exists? Who will decide on the course of action? Who will direct the mission and determine when mission changes are to be made? Who will determine if the mission was successful? And perhaps most important, who will pay for this work? And there are many more questions.

The U.S. military has long struggled with these command and control issues that now confront the NEO community. Earlier, I noted a concept of operations for the first step in NEO mitigation–a Natural Impact Warning Clearinghouse. I believe this command and control operation could catalog and provide credible warning information on future NEO impact problems, as well as rapidly provide information on the nature of an impact.

International Issues: NEO impact mitigation should be an international operation. In my opinion, the United States should proceed carefully in this area. International space programs, such as the International Space Station, fill many functions. A NEO mitigation program would have only one objective. In my view, a single responsible nation would have the best chance of a successful NEO mitigation mission. The responsible nation would not need to worry about giving up national security sensitive information and technology as it would build and control the entire mission itself. As I have pointed out, the means to identify threats and mitigate them overlap with other national security objectives.

It does, however, make sense that the data gathered from surveys and in situ measurements be shared among all. This would maximize the possibility the nation best-positioned to perform a mitigation mission would come forward. One of the first tasks of the Natural Impact Warning Clearinghouse noted above could be to collect and provide a distribution point for such data.

Roles of the U.S. Military and NASA: Currently, NASA has been assigned the task of addressing some NEO issues. The U.S. DoD has been asked to assist this effort. However, the U.S. DoD has not been assigned tasks, nor has any item relating to NEOs been included in military operational requirements. I believe one option would be for the U.S. DoD to assume the role of collecting available data and assessing what, if any, threat might exist from possible NEO collisions of all sizes. This does not mean other groups, in particular the international scientific community, should not continue their independent efforts. However, the U.S. DoD is likely, for the foreseeable future, to have most of the required sensors to do this job. Moreover, in my view, the U.S. DoD has the discipline and continuity to ensure consistent, long-term focus for this important job. As a consequence of this function, the U.S. DoD might collect a large quantity of important scientific data. To the degree that the vast bulk of this has no military security implications, it could be released to the international scientific community.

In addition, I believe NASA should continue the scientific task of assessing the nature of NEOs. Performing the necessary scientific studies, including missions to NEOs to gather data, is among NASA's responsibilities. Like the 1994 U.S. DoD/NASA Clementine probe, these missions could serve as important technological demonstrations for the U.S. DoD, and might be conducted jointly with NASA.

Should a threatening NEO be discovered, it is my opinion the U.S. DoD could offer much toward mitigating the threat. Of course, with a funded and focused surveillance program for cataloging and scientific study as outlined above, we should have ample time to debate this issue before it becomes critical.

Summart: NEO mitigation is a topic whose time has come. I believe various aspects related to NEO impacts, including the possibility that an impact would be misidentified as a nuclear attack, are critical national and international security issues. The focus of NEO mitigation efforts–in finding and tracking them, and in exploring and moving some–should shift to smaller objects. The near-term threats are much more likely to come from these "small" objects (100 meters in diameter or so) and we might be able to divert such objects without recourse to nuclear devices.

After a suitable class of NEOs is found, microsatellite missions to explore and perhaps perform test divert operations could be considered. The technologies for low-cost NEO missions exist today.

The necessary command and control, sensor and space operations technologies and equipment are all "dual use" to the military. In my view, it stands to reason that strong military involvement should be considered in a national and international NEO program.