NSF's National Optical Infrared Astronomy Research Laboratory and Planetary Science

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NSF's National Optical Infrared Astronomy Research Laboratory (NOIRLab) is a new organization that consolidates NSF's National Optical Astronomy Observatory (NOAO), the Gemini Observatory, and the operation of the Rubin Observatory into a unified system for providing the US research community with frontier observational facilities and data. NOIRLab will also be tasked with providing the community with access to the US extremely large telescope (ELT) projects now in development: the Giant Magellan Telescope and the Thirty Meter Telescope, if the NSF invests in construction and/or operations of one or both of these telescopes

Historically, NOAO and Gemini have enthusiastically supported planetary science research, and fully expect to continue to do so over the coming decade. The Rubin Observatory will soon begin operations with its Legacy Survey of Space and Time (LSST), which will provide a deep census of small bodies throughout the solar system. The ELTs will be built around high-performance adaptive optics fed imaging and spectroscopy, which will be available for detailed study of all solar system objects, and will support strong programs in exo-planet research.

The Decade Ahead

We write to the Planetary Science and Astrobiology Decadal Survey with the simple goal of requesting that the survey consider us within the constellation of facilities available for supporting initiatives in planetary science and astrobiology over the coming decade. Overall, we see NOIRLab supporting leading-edge planetary science research with all of its facilities, and would enjoy working with the planetary science community to realize this ambition.

In the near term over the next few years, the NOAO Kitt Peak (KPNO), WIYN, Cerro Tololo (CTIO) and SOAR facilities, now configured as the NOIRLab Mid-Scale Observatories (MSO), will continue to provide public access and data obtained with 1-m to 4-m telescopes. For the last several years CTIO has operated the Dark Energy Camera (DECam) at the CTIO Blanco 4-m telescope, which offers wide-field and deep CCD imaging. This instrument has proven to be extremely powerful for discovering small solar system bodies and will remain available for surveys proposed by the community.

At KPNO we have begun commissioning the Dark Energy Spectroscopic Instrument (DESI) at the Mayall 4-m telescope for a multi-year wide-field spectroscopic survey. Use of the instrument after completion of the survey is presently under consideration. At the WIYN telescope we will soon begin operating the NEID spectrograph (NASA/NSF-explore Exoplanet Investigations with Doppler spectroscopy), which has the goal of discovering earth-like exoplanets with ultra-high precision radial velocity observations.

The Gemini Observatory will likewise continue to offer 8-m telescopes in the north and south with strong optical, NIR and mid-IR instrumentation to the community. Instruments can be paired with adaptive optics for high-resolution programs.

The Rubin Observatory has submitted its own white paper, "The Scientific Impact of the Vera C. Rubin Observatory's Legacy Survey of Space and Time (LSST) for Solar System Science," which discusses in rich detail the high impact that its program should have on the science of small solar system bodies. A key part of the successful realization of this program will depend on close interaction of the community with its data and operation. Apart from operation of the LSST, NOIRLab will also be hosting the Antares "event broker," which flags transient sources detected in the LSST. While most of its focus will be on transients created by astrophysical processes, the event stream will also capture solar system objects.

NOIRLab also offers its Data Lab of archival imaging and spectroscopic surveys, as well as a deep full-sky source catalogue. These holdings include all DECam images, as well as earlier generation Mosaic imaging surveys. Data Lab further provides an environment for in-situ exploration and analysis of the data holdings.

Evolution of NOIRLab facilities over longer timescales will be driven by the needs of the community and will depend on input received from the presently ongoing Astronomy and Astrophysics Decadal Survey and the Planetary Science and Astrobiology Decadal Survey. Our ability to address observational problems addressed by these surveys will be enhanced with an explicit citation to the role that we can play in advancing planetary science in the coming decade.

A Sample of Planetary Science Work Done with NOAO and Gemini Observations

In support of our argument that NOIRLab can support future planetary science work, we cite some planetary work already accomplished with NOAO and Gemini observations, prior to their recent integration into NOIRLab. We start with research conducted using the CTIO DECam and KPNO Mosaic-II imagers, which have been extremely handy for assessing the properties and populations of small solar system objects, such as asteroids, irregular satellites of the gas and ice giant planets, as well as distant Kuiper Belt objects (KBOs), dwarf planets, and comets. When stars or galaxies are the target of a survey, it's always possible to trade telescope aperture against camera field of view to reach a needed survey depth and area in a given amount of time. With moving solar system objects, however, the depth of a survey is really just set by the aperture.   As such, large-field imagers on 4-m class telescopes can probe populations of small objects in the solar system that are simply not visible with smaller apertures.

In the previous decade, Elliot et al. (2005) used the Mosaic imager at the Mayall 4-m to provide the first rich census of KBOs and the structure of the Kuiper Belt.   This leading capability has continued with DECam and Mosaic II. Trilling et al. (2017) used DECam to probe the population of near-earth objects (NEOs), which includes the population of objects that are potentially hazardous to the Earth.   From the large sample of NEOs that they discovered, they provided solid constraints on the overall numbers of NEOs in the solar system from those that are 1 km in size to those as small as 10 m, finding that the abundance of NEOs smaller than ~200 m was actually an order of magnitude smaller than assumed prior to the survey.

Moving further out, Sheppard et al. (2018) used DECam to discover 12 new small outer satellites of Jupiter, upping its total number of known satellites to 79. The orbital properties of these satellites contain fossil information on the early orbital evolution of Jupiter and its interaction with other bodies in the forming solar system. Gerdes et al. (2016) used DECam to discover two new Neptunian Trojan objects. Both objects are in relatively eccentric and inclined orbits for Trojans, supporting the picture that Neptunian Trojans are dynamically hot. As with Jupiter, this provides information on how Neptune interacted with objects in the outer solar system over its history.

The outer edge of the Kuiper Belt appears to occur at ~50 AU out from the Sun, but deep surveys, including those made with DECam, have found small solar system bodies with even larger orbits well beyond this zone.   These objects do not appear to trace out any sort of a disk, as do the KBOs, and their existence poses questions as to how these bodies formed in the solar nebula in the first place. A pressing problem of recent attention has been whether or not this outer-zone may host truly massive undiscovered planets exceeding even the mass of the Earth. Trujillo & Sheppard (2014) used DECam to discover 2012 VP113, which has a perihelion distance of 80 AU, the largest known of any solar system object. Trujillo & Sheppard noted the coincidental alignment of the orbit of this object with the orbits of the small set of other objects discovered beyond the Kuiper Belt, and suggested that this was evidence for the gravitational influence of a massive planet at even larger distances. This has led to a strong effort to survey for additional objects beyond the Kuiper Belt, as well as for direct detection of an unknown planet in its own right. DECam has played a central role in these searches. While no new planet has yet to be detected, Sheppard et al. (2016) did use DECam to find two new small bodies with orbits well outside the Kuiper Belt that with 2012 VP113 are part of the family of objects with aligned orbits.

While for many solar system programs the main motivation is simply to find the small bodies that define an important population of objects, given how quickly our understanding of the solar system is evolving, other programs seek detailed characterization of objects recently discovered.   A great example of this work was provided by the photometric investigation of the first interstellar object known to have entered the solar system, 1I/2017 U1 ‘Oumuamua, by Belton et al. (2018).   These investigators used WIYN and other telescopes to obtain light curves of this novel object, providing evidence that it has an unusually elongated shape.

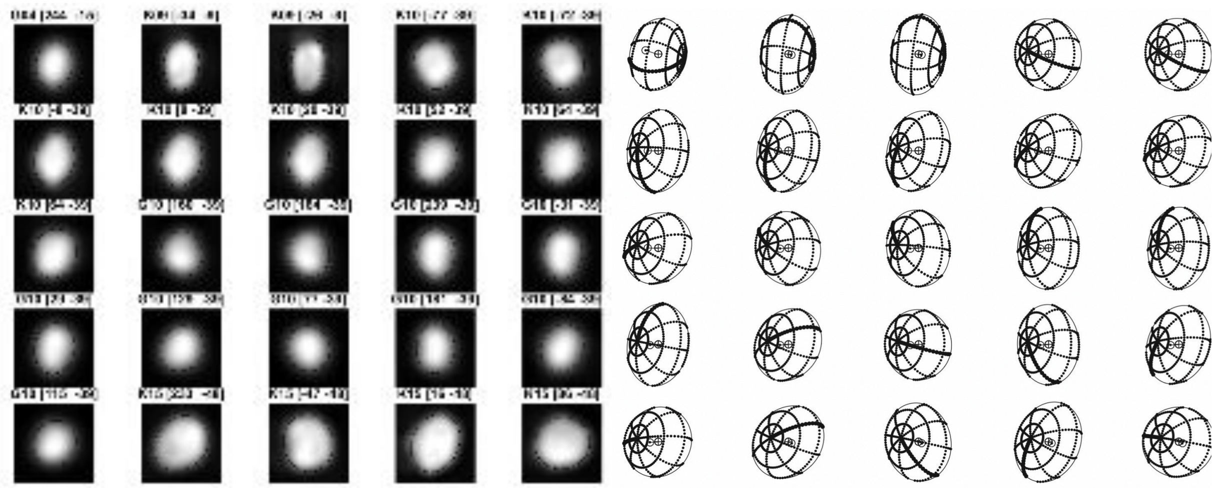

Figure 1. *Left*: Deconvolved Gemini/NIRI and Keck/NIRC2 images of asteroid 16 Psyche. Each image is labeled with the initial of the observatory and the two-digit year it was taken; the rotational phase and sub-Earth latitude during each observations are shown in brackets; the sub-Earth latitudes are negative in all cases. The black outlines (difficult to see) show the best-fit ellipse for each image. *Right*: Orientation during each observation shown in left panel of the best-fitting triaxial model; the south pole and equator are visible in all cases. Sub-Earth and sub-Sun points are labeled as ⊕ and ⊙, respectively. [Figures reproduced from Drummond, et al. 2018.]

Turning to examples of planetary science done with Gemini observations, we start by highlighting its support of a future mission, and its adaptive optics (AO) capabilities. NASA's planned Psyche Discovery Mission will be visiting the Main Belt asteroid 16 Psyche, one of the defining members of the metallic M-class asteroids. It is scheduled for launch in 2022, with orbital insertion four years later. Data acquired using the Near InfraRed Imager (NIRI) with the Altair AO system at Gemini North and the NIRC2 camera with the AO system on the Keck II telescope allowed Psyche's figure to be obtained in advance of the mission. Drummond et al. (2018) carried out an analysis on a set of 25 images taken with adaptive optics on six different nights spanning four oppositions of Psyche from June 2004 through December 2015. Because the rotational period of Psyche is 4.2 hours, observations from the same night can sample significantly different orientations. The images were processed using parametric blind deconvolution, then fitted simultaneously using a triaxial ellipsoidal model incorporating the known orbit and rotation of Psyche. Figure 1 shows the 25 deconvolved AO images and the best-fit model as it would have appeared at the time of each observation. Psyche has an obliquity of 95°, so it rotates "on its side," and its shape is distinctly non-spherical. The analysis yields triaxial ellipsoid dimensions of (a,b,c) = (274 ± 9, 231 ± 7, 176 ± 7) km and leads to an estimated density of 4.2 ± 0.6 g/cm^3. This density is considerably less than that of pure nickel-iron and would require a porosity of 47% if the bulk composition is the same as its surface. That is to say, Psyche appears to be full of holes. Instead of a solid iron core, it may be a disrupted and re-assembled heap of scrap metal. Porosities of some "rubble pile" asteroids are known to be this large, but none have such high metal contents. Alternatively, Psyche could be a stony-iron asteroid with low porosity and an interior much more silicate-rich than its surface, but such an inverted structure would be difficult to understand.

Gemini's adaptive optics capability has also been used to great effect to study the gas and ice giants, and their moons. For example, ever since the Voyager spacecrafts revealed rampant volcanism on Jupiter's innermost large moon Io, planetary scientists have puzzled over the variations in the timing and intensities of the satellite's many eruptions. To understand what drives the variations in the volcanism on Io, de Kleer et al. (2019) analyzed a set of observations collected between August 2013 and July 2018 using (NIRI) on Gemini North with the ALTAIR AO system in natural guide star (NGS) mode and the Near Infrared Camera 2 (NIRC2) on the Keck II telescope, also using NGS adaptive optics. The Gemini/NIRI data comprise 80% of the total visits; example NIRI images are shown in Figure 2.

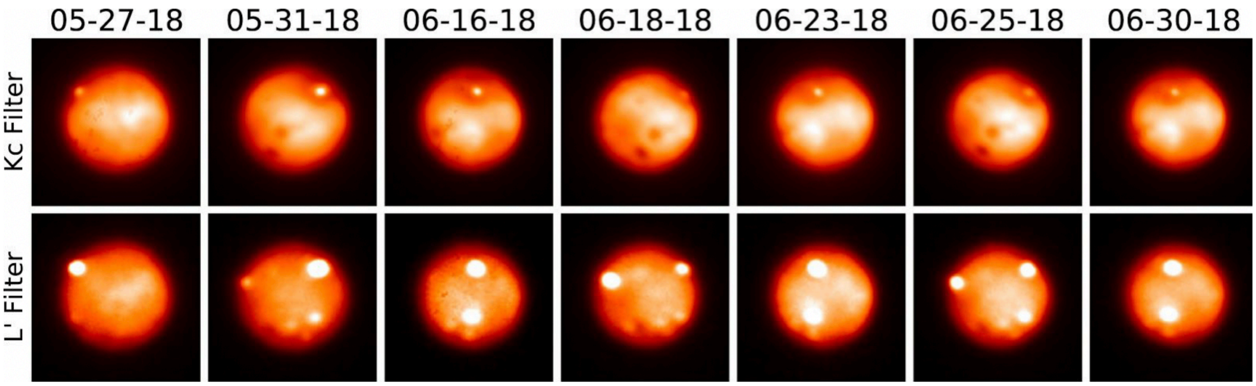

Figure 2. AO-assisted near-IR images taken with NIRI on Gemini North of Jupiter's moon Io, showing the eruption of Isum Patera in May and June 2018. Isum Patera is the only bright spot visible in the moon's northern hemisphere in the K-continuum (2.27 µm) images; it is seen at the corresponding locations in the L' (3.78 µm) images. The bright spot south of Isum Patera in all the L' images is Marduk Fluctus. [Credit: de Kleer et al., AJ, 158: 29, 2019.]

De Kleer et al. (2019) detected at least 75 unique hot spots of volcanic activity. The most active volcano, Loki Patera, was detected 113 times during the five-year campaign, essentially every time it was visible. Three other hot spots were each detected at least 80 times. Loki Patera appears to be erupting continuously, but its brightness in the near-infrared varies by more than an order of magnitude. This large data set enabled the team to uncover surprising patterns in Io's volcanic activity. For instance, of the 18 sites with the brightest eruptions, 16 are on the trailing hemisphere with respect to Io's orbital motion. This tendency remains unexplained; the likelihood of it occurring from a random spatial distribution is much less than 1%. De Kleer et al. show that the roughly 500-day variations in the intensity of Loki Patera's activity may be related to periodic changes in the shape of the moon's orbit. Regular gravitational perturbations from Europa and Ganymede, which respectively have 2:1 and 4:1 orbital resonances with Io, prevent the inner moon's orbit from circularizing. Instead, Io's eccentricity and semimajor axis vary cyclically with periods of 480 and 460 days, respectively. This evolution in Io's orbit is consistent with the timescale of the quasi-periodic behavior of Loki Patera.

At first, this link between orbital evolution and volcanic activity may seem surprising, since the range in the tidal stresses over a single orbit is larger than the variation in the mean tides resulting from the change in orbital shape. However, the researchers note that while magma is likely too viscous to change its flow significantly on the timescale of one orbit, it can adjust its flow over the longer period associated with the change in Io's orbital shape. If there is a connection, the peak in activity should coincide with the time of maximum orbital eccentricity. The data confirm that this is indeed the case.

Gemini NIR spectroscopy has provided direct information on the atmospheres of the gas and ice giant planets. For example, despite decades of observations, including a visit by Voyager 2 in 1986, the detailed composition of the clouds on Uranus (and Neptune) has remained uncertain. However, observations obtained with the Near-Infrared Integral Field Spectrometer (NIFS) on Gemini North have finally confirmed that hydrogen sulfide (H_2S) is a key component of those clouds (Irwin et al. 2019). There has been a long-standing debate over the composition of Uranus's clouds and whether hydrogen sulfide or ammonia dominate the cloud deck, but definitive evidence was lacking either way. This is no longer the case.

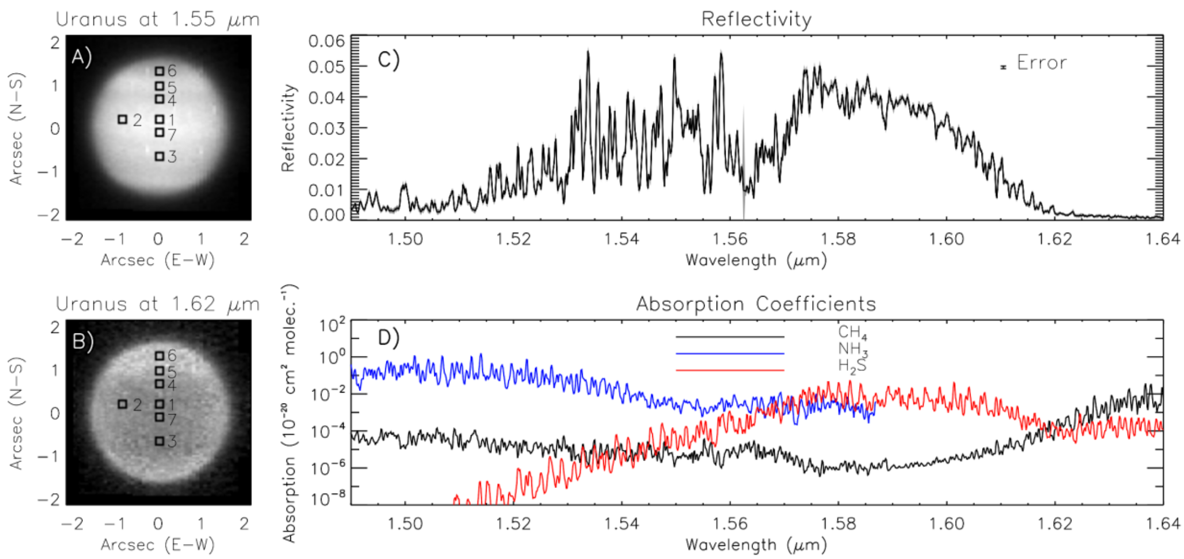

Figure 3. The appearance and spectrum of Uranus at the wavelengths observed by Gemini/NIFS and associated absorption spectra of CH4, NH3 and H2S. Panel A: The appearance of Uranus at 1.55 µm (low methane absorption, showing reflection for cloud/haze at all vertical levels), showing the position of the seven 5×5 pixel test areas used for analysis. Panel B: The appearance of Uranus at 1.62 µm (high methane absorption, showing reflection from upper atmospheric haze only). Panel C: Reference spectrum of Uranus averaged over area '1' (in Panel A) near the center of the planet's disk, just north of the equator. Panel D: strength of the model absorption coefficients derived over the Gemini/NIFS spectral range for conditions found at the tops of Uranus' main visible clouds. [Figure reproduced from Irwin et al., *Nature Astronomy*, 2018.]

The Gemini observations, shown in Figure 3, sampled reflected sunlight from a region immediately above the main visible cloud layer in Uranus's atmosphere. The detection of hydrogen sulfide high in Uranus's cloud deck (and presumably Neptune's) contrasts sharply with the inner gas giant planets, Jupiter and Saturn, where the bulk of the upper clouds are comprised of ammonia ice, and no hydrogen sulfide is detectable. These differences were likely imprinted within the proto-solar nebula, where the balance between the amounts of nitrogen and sulphur (and hence NH_3 and H_2S) was determined by the temperature, and thus the location, of a given planet's formation. When a cloud deck forms by condensation within the atmosphere of a planet, it carries information about the gas locked away deeper in the atmospheric reservoir.

The results of this study set a lower limit to the amount of H_2S in the upper atmosphere of Uranus. The study also confirms that this far-flung world is fertile ground for probing the early history of our solar system and perhaps understanding the physical conditions on other large, icy worlds orbiting the stars beyond our Sun.

A Closing Thought

The coming decade will continue to be an exciting time of discovery. The scientists and engineers of NOIRlab look forward to helping the community of planetary scientists make it so.

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