GeminiFocus

June 2010 Publication of the Gemini Observatory

On the cover: Montage of stunning Gemini Observatory Legacy Images

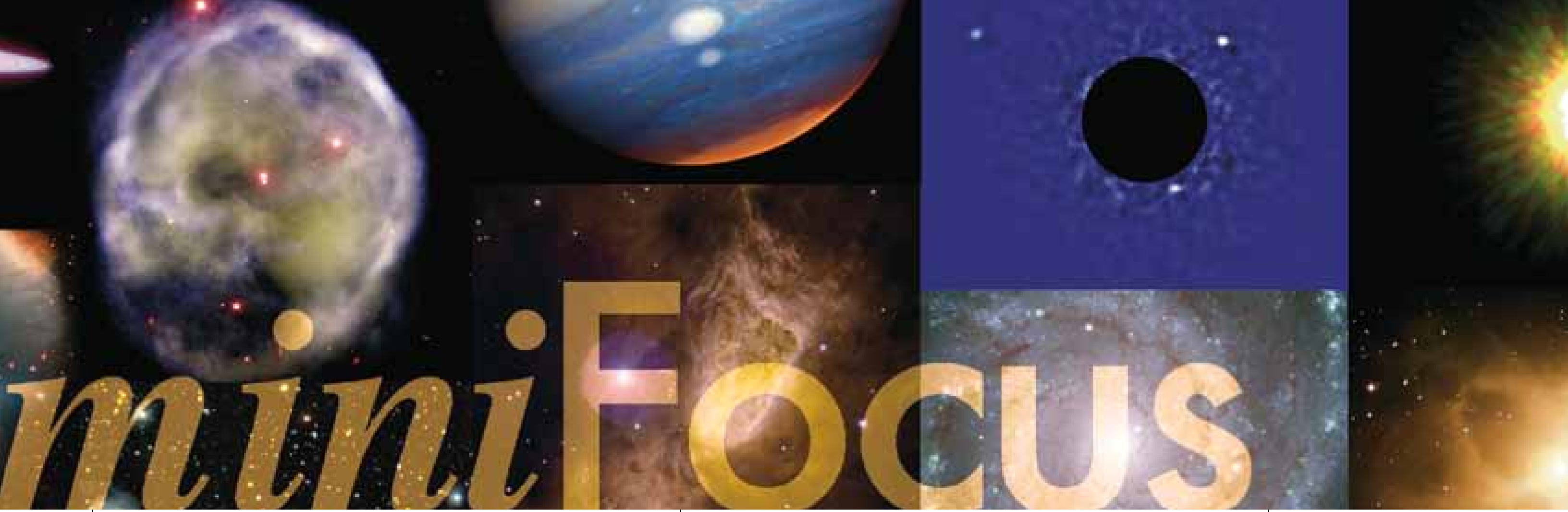
Special Section:
Gemini's First Decade of Discovery

This issue of *Gemini*Focus celebrates Gemini's first decade of science operations with a special section highlighting many of the observatory's accomplishments. It includes not only articles on the scientific, engineering and operational breakthroughs and achievements (starting on pages 6, 48, and 54 respectively), but also a stunning gallery of images (staff favorites) from the Gemini Legacy collection (starting on page 60). Key science results are presented in the following areas:

The editors hope you enjoy this section as much as we have enjoyed assembling it. We look forward to another productive decade of discovery at Gemini as our users find exciting new ways to push the boundaries of knowledge and technology.

–The Editors

Managing Editor, Peter Michaud • Associate Editors, Carolyn Collins Petersen and Stephen James O'Meara • Designer, Kirk Pu'uohau-Pummill


miniFocus

10 Years of Science, Technology, & Operations

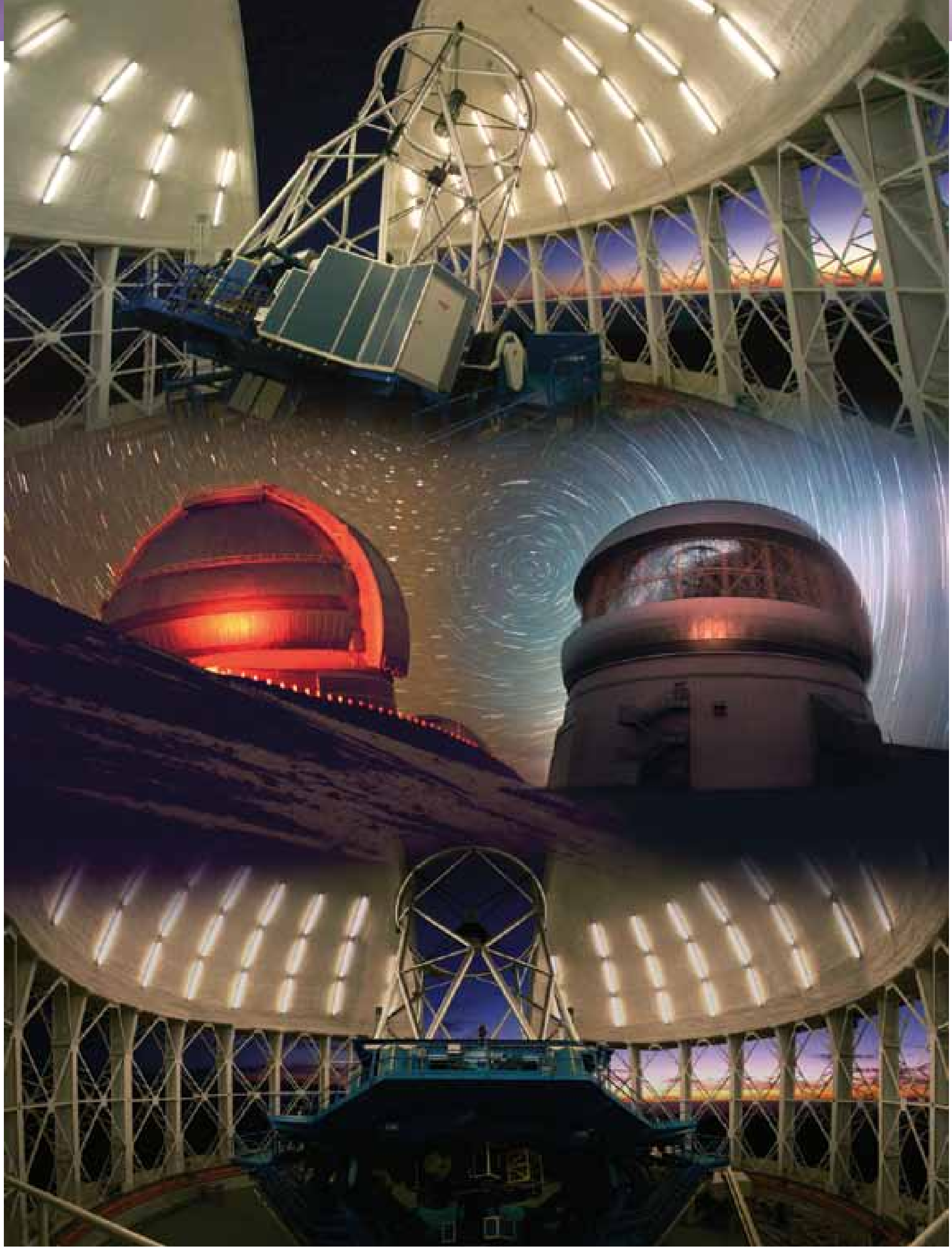
When Gemini was just beginning science operations, the U.S. Presidency was in transition from Bill Clinton to George W. Bush, the term "911" did not carry any terrorist connotations, and I had one less child. A lot has happened in the world and at Gemini since then. In this special 10th anniversary edition of *Gemini*Focus, we commemorate and celebrate a decade of progress, including an enormous range of accomplishments in astronomical research, telescope technology, and operations.

Roughly 10 years ago, the first photons from a distant star were "harvested" by Gemini North's primary mirror and crudely aimed into a region a bit smaller than a fingernail at the mirror's prime focus. This milestone (reached but once in the lifetime of any observatory and quietly experienced by Gemini's small commissioning team), signaled the start of an incredible sequence of events over the next decade. Within about a year, the mirror's focus would be sharpened by many orders of magnitude as those first splotches of starlight were directed into images featuring Airy rings and diffraction-limited cores. This new triumph, which involved a complex blend of active and adaptive optics, showcased for the world what modern electro-optics technologies could do for astronomy in the 21st century. Grounded in this achievement, first light at Gemini South soon followed, portending unprecedented all-sky access from the ground using these two amazing machines.

Meanwhile, the first in a series of modern instruments arrived at Gemini. Collectively, they were capable of harnessing light across a wavelength range spanning nearly a factor of 100, offering Gemini's community a wealth of observing options, including multi-wavelength imaging, single and multi-slit spectroscopy, integral-field spectroscopy, and natural and laser guide star adaptive optics. Gemini's burgeoning operations developed in parallel with the arrival of this impressive new instrumentation, leaping ahead with a multi-instrument queue designed to match the best science applications with observing conditions. Gemini's queue-based operations, unprecedented in optical/infrared astronomy on such a large and complex platform, defied widely held expectations. This demonstrated that it's possible to optimize program selection with site conditions while also reaching competitive open shutter efficiencies, acquisition times, and startling new Target of Opportunity capabilities. So began the era of Gemini's science operations. Now we look toward a bright future through a powerful "lens" forged through our past accomplishments.

At the dedication of the Gemini North telescope on Mauna Kea in June 1999, former U.S. National Science Foundation director Rita Colwell said, "We stand here on the brink of discovery that we cannot even imagine. We can only be sure that these discoveries will enlarge our vision and make our spirits soar in this thin air and beyond."

Now, as we celebrate Gemini's 10th year of scientific discovery, there can be no doubt about the truth and prophetic



insightfulness of her words. In fact, it's sometimes difficult to appreciate how far we've come in only one decade. With over 750 scientific papers published (using Gemini data, as of April 15, 2010), hundreds of scientific users spanning the globe, a successful queue-based operational model unique among ground-based observatories, and technical and engineering milestones like protected silver mirror coatings, Gemini is entering a truly mature stage as an astronomical research facility.

It is this transition into a well-established scientific research tool that we celebrate with this issue of *Gemini*Focus. In the pages that follow, the editors of this publication and the staff of the Gemini Observatory hope you will appreciate the highlights featured herein. Every success, and every challenge overcome, reflects the work and dedication of our staff and international community, who have dedicated themselves to Gemini's vision. The stories told here (and the myriad stories we had to exclude) serve as an inspiration to the future potential of our observatory, a future that will continue to "… enlarge our vision and make our spirits soar…"

Doug Simons, Director

A Celebration of Data

Above left: The Gemini North facility on Mauna Kea with the summer Milky Way and Galactic Center overhead.

Above right: Close-up of IRS-8 revealing the fast moving star and bow-shock

Facing page: Entire Gemini Galactic Center field from a mosaic of images covering about 40 x 40 arcseconds and obtained with the Hokupa'a adaptive optics system for the Gemini North Demonstration Science program.

A decade ago, on several evenings during July and August 2000, the Gemini North telescope silently slewed toward the Galactic Center in the direction of the constellation Sagittarius. The goal: to capture a small quantity of near-infrared photons that would result in the first significant scientific data from the Gemini Observatory. These hard-earned photons, when treated as waves, were brought into pinpoint focus with a deformable mirror in the Hokupa'a adaptive-optics system, and then, nearly instantly turned into electrically-charged data by the detector in the QUIRC near-infrared camera. Both of these instruments (Hokupa'a and QUIRC) were on loan from the University of Hawaii's Institute for Astronomy prior to the delivery of facility instrumentation originally envisioned to produce Gemini's first science.

Called "Quick Start," or the Gemini North Demonstration Science program, these Galactic Center data (see images on facing page and above right) would appear in a variety of publications, including some of the most heavily cited papers from Gemini data, and provide the impetus for the legacy of Gemini data to follow.

As the widest adaptive optics view of the Galactic Center ever obtained, this mosaic included one target that immediately sparked interest. Known as IRS-8 (Infrared Source 8 from the InfraRed Astronomy Satellite, IRAS), this object had previously only been resolved as a featureless blob. But now, with adaptive optics on Gemini, its form was obvious. IRS-8 revealed itself to be a high-velocity star being flung around by the Milky Way's central supermassive black hole. As the hapless star rides the curvature of space-time, it plows through and heats up interstellar neutral hydrogen, causing it to glow in the form of a bow-shock (see image above right).

The next 40 pages feature a selection of top science results from Gemini taken since this first data became available to astronomers. Some data are from studies in areas never dreamed of when Gemini was envisioned. Other data provide new perspectives on existing fields of study that have puzzled astronomers for decades. Wherever Gemini's science goes in the future, it is this data from several evenings in the Northern Hemisphere's summer of 2000 that began our journey. Based on the data amassed by Gemini during the past decade, there's a lot to look forward to over the next decade and beyond.

Monitoring the Solar System

Due to their relatively close proximity, transient events in our Solar System can be extremely compelling because we can watch them in great detail and over time frames that are generally short. However, many of the most interesting events are completely unpredictable. An effective program that identifies potential Targets of Opportunity (ToO) is a must. During the past 10 years, Gemini has established a model ToO program that ranges from the timely study of weather on nearby planets and moons to Gamma-ray Bursts (GRB) at the very edge of the observable universe (see article starting on page 44). Gemini's multi-instrument queue provides a unique strength that allows observations at literally a moment's notice and with a diverse assortment of instrumentation ranging from optical through mid-infrared imaging and spectroscopy. Furthermore, the geographical distribution of the two Gemini telescopes provides better temporal coverage due to the 6- to 7-hour time difference between Gemini North and South (this is especially relevant for solar-system objects on the ecliptic, since they are visible to both telescopes over the course of any given night).

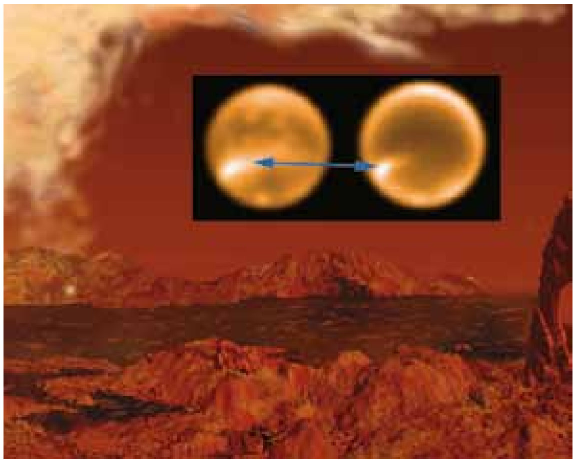
Figure 1: (above), Gemini North adaptive optics image of Jupiter in the near infrared showing the Great Red Spot (and "Red Spot Junior" below) as white ovals. This image was obtained on July 14, 2006, when both storms were aligned on Jupiter's meridian.

So, it's not surprising that time-dependent, solar-system observations are featured heavily in Gemini's nightly logs and ultimately in highly cited scientific papers. One of the most cited and publicized of these is the ongoing ToO program headed by Henry Roe (Lowell Observatory) to monitor and observe the weather on Saturn's moon Titan. This program, in operation since the first Hokupa'a images of Titan in December 2001 (however, this was not a ToO program at that time), is a model of the effective use of diverse resources. Figure 3 shows a short-lived weather feature observed in the clouds of Titan in 2004 thought to have been caused by a surface cryovolcanic feature. The current ToO program features regular global monitoring of Titan's atmosphere with the NASA InfraRed Telescope Facility (IRTF), a new dedicated 0.5-meter robotic telescope at Lowell Observatory in Flagstaff Arizona, a data pipeline to provide alerts, and the use of both Keck and Gemini's adaptive-optics technologies to furnish rapid and detailed follow-up observations when a weather event is detected.

This is exactly what happened in April 2008. A brightening of Titan's near-infrared signature was detected by the IRTF on the night of April 13. Observations using the Gemini North Altair adaptive optics (AO) system with the Near-Infrared Imager (NIRI) were made on the very next night. This event (see Figure 4, page 10) was the brightest weather event the team had ever detected.

Figure 2: (above), Gemini North near-infrared image of Saturn and Titan. Image obtained on May 7, 2009, using the Altair adaptive optics system with the Near-InfraRed Imager (NIRI).

Figure 3: (right), Artist's conception of a methane cryovolcano/geyser on Titan with Gemini's Altair adaptive optics images (inset) with clouds (right) and surface features (left) indicated by blue arrow. Gemini background artwork by Jon Lomberg.



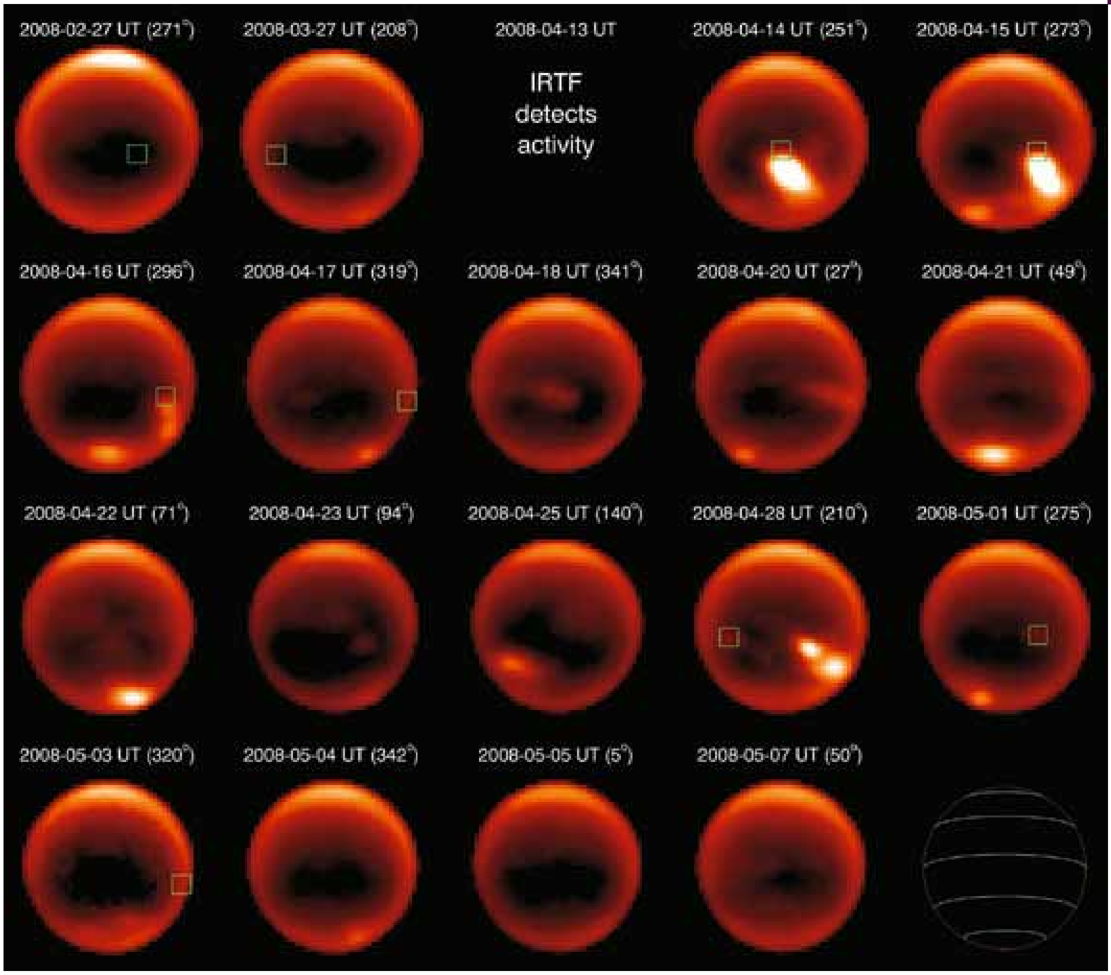
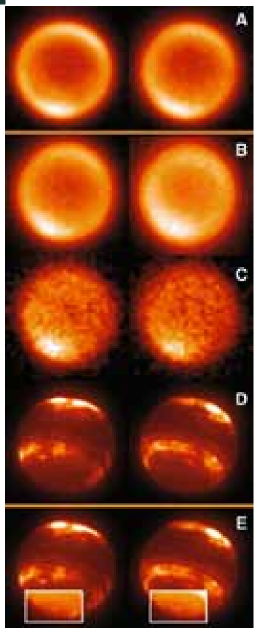


Figure 4: Gemini North near-infrared AO images highlighting the variable bright clouds and more static high stratospheric haze. On March 27, 2008, there were essentially no clouds present. The green box indicates the initial location of the large storm. The original storm rotates to the night side of Titan after a few days with Titan's 16-Earth-day rotational period.

However, the circumstances of this event were unusual and unexpected. When Emily Schaller (a Caltech graduate student at the time) received the IRTF spectra, the magnitude of the event made her skeptical at first. Her skepticism soon led to excitement when it became apparent that this event was real and represented an unprecedented storm on Titan. She immediately alerted her colleagues to trigger the Gemini ToO observations. The resulting Altair/NIRI observations showed that the new methane-based weather feature was located in the tropics of Titan where the existence of a mostly desert climate was thought to exist. Furthermore, the energy of the event triggered atmospheric planetary waves that traveled to other latitudes on Titan, a process very similar to that which occurs in the Earth's atmosphere.

On a larger scale, the outer planet Neptune displays a variety of weather features like those on gas giants, and which are extremely latitude dependent. A mid-infrared program using the MICHELLE spectrograph/imager and headed by Heidi Hammel (Space Science Institute), probed stratospheric ethane and methane emissions and produced the first published mid-infrared images of Neptune. Corresponding W.M. Keck Observatory near-infrared AO images complement these Gemini mid-infrared data, which were both obtained on July 4-5, 2005. These data (see Figure 5) showed no correlation between the stratospheric features in the Gemini images and the tropospheric clouds detected in the near-infrared Keck observations. Instead, the emissions came predominantly from the south polar regions, and were much like those found on Saturn. It was initially a surprise to find this similarity to Saturn, given the differences between the two worlds. However, astronomers are now starting to suspect that the polar regions on all four giant planets harbor interesting dynamical structures.

July 4, 2005, was a busy 24-hour period at Gemini North. As data for the Hammel et al. Neptune research (above) was being obtained, astronomers from around the world were ascending to the summit area of Mauna Kea to participate in a very different type of solar-system observation program. This time, astronomers were monitoring an explosive event made possible by a demolition-style cometary collision. Called Deep Impact, the mission sent a spacecraft



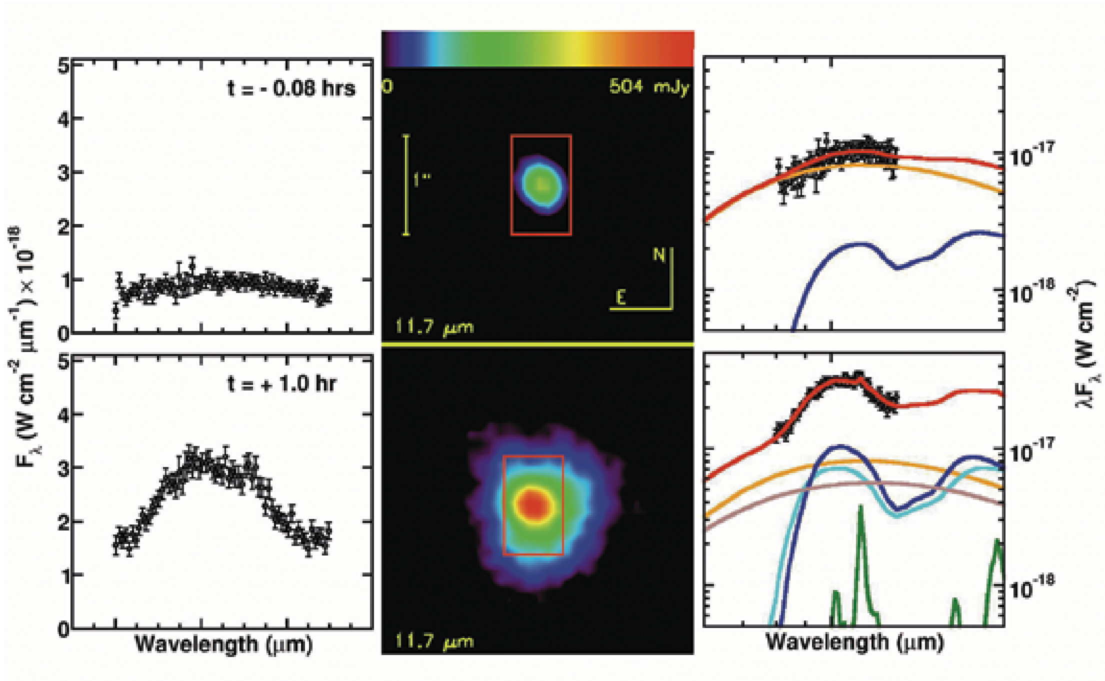


Figure 5: (above left), Neptune images at mid- and near-infrared wavelengths obtained in July 4-5, 2005, with the mid-infrared imaging capabilities of MICHELLE on Gemini North (A,B, and C) and near-infrared (NIRC2) AO images from the W.M. Keck Observatory (D), with polar regions enhanced in (E).

Figure 6: (above right), Imaging and spectroscopy of two temporal epochs of Comet 9P/Tempel 1 obtained before and after the Deep Impact collision.

to Comet 9P/Tempel 1 (9P) and sacrificed both the spacecraft and a washing machine-sized impactor which violently collided with the comet's nucleus and stirred up its subsurface. Gemini led in the mid-infrared observations of this event both before the collision and after it successfully spewed up debris from inside the comet and dispersed a core sample for all to see and study. When the results came in, the Gemini MICHELLE observations (Figure 6), combined with observations from the W.M. Keck, Subaru, and other observatories revealed a peak flux at 11.2 microns due to emissions from relatively transparent (i.e., poorly absorbing), magnesium-rich crystalline olivine. Models fitted to the data suggest that a composition of amorphous carbon, pyroxene, olivine, and magnesium-rich crystalline olivine were all present and that grain size distribution peaked at 0.2 micron.

The unique Gemini data set from the Deep Impact event also allowed for a time-of-flight analysis, in which it was found that grains were being released from the nucleus for about an hour after the impact. Different minerals traveled at various speeds, implying that the nucleus of the comet is inhomogeneous. The Gemini data provided the only means to produce an estimate of the total ejected mass of the impact, which came out to be about 1.5×10^6 kilograms an hour after the impact. This is approximately equivalent to 25 fully loaded tractor-trailer trucks. Two highly cited papers, including one in the journal *Science*, were generated by the Gemini team led by David Harker (University of California, San Diego) and Chick Woodward (University of Minnesota).

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Exploring Small & Distant Bodies in the Solar System

The International Astronomical Union's (IAU) decision in 2005 to demote Pluto from a full-fledged planet to a dwarf planet was based on discoveries about the outer solar system that would also have a profound impact on the scientific legacy of the Gemini Observatory (not to mention what it would do to elementary school mnemonics). Although the decision about the definition of a "planet" was not limited to the outer reaches of the Solar System (the main-belt asteroid Ceres was also promoted to a dwarf planet), much interest and effort have been directed toward the understanding of trans-Neptunian worlds. Potentially, the non-cometary bodies of the outer solar system could be more plentiful than ever imagined and, over the past decade, Gemini has played a significant role in the early characterization of these icy worlds locked in a deep freeze far from the warmth of the Sun.

Gemini's entrance into the realm of outer solar system studies began in 2001 with Hokupa'a adaptive optics imaging of Pluto and its moon Charon. However, the real science began in 2004 shortly after a research team (including Gemini astronomer Chadwick Trujillo, California Institute of Technology (Caltech) astronomer Michael Brown, and David Rabinowitz of Yale University) discovered a small new planet-like body some 12.9 billion kilometers (8 billion miles) from the Sun. As the most distant planet-like object ever observed in the solar system, this world hinted at the need to establish a new class of smaller solar-system bodies. Otherwise, the class of planets might grow too unwieldy. Observations of this extremely distant icy dwarf planet (later dubbed Sedna, after the Inuit goddess of arctic sea life) would require the world's

Figure 1: Artist's conception of what Eris (2003 UB 313) might look like from its distant post in the Solar System. Gemini artwork by Jon Lomberg

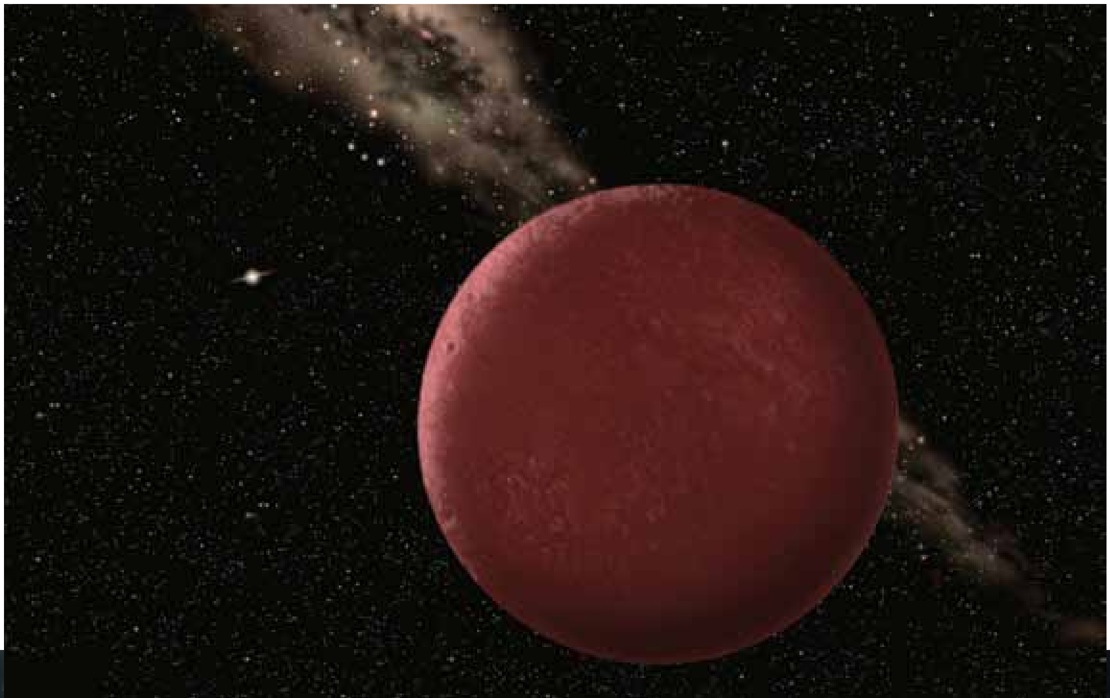
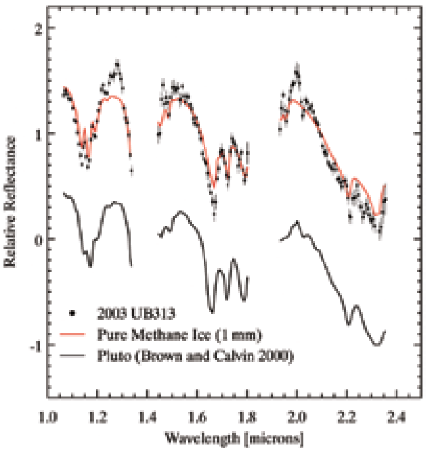


Figure 2: Artist's conception of Pluto and Charon, showing Charon's possible plume activity. Gemini artwork by Mark C. Petersen, Carolyn Collins Petersen (Loch Ness Productions) and Richard Wright (SoftwareBisque)

largest telescopes to begin characterizing its surface. Of course Gemini was uniquely suited to play a central role in the analysis of this new world (and others soon to be discovered) due to its infrared sensitivity.

The Gemini Near-Infrared Imager (NIRI) on Gemini North, in its spectroscopic mode, obtained the first near-infrared spectra of Sedna in December 2003. Largely featureless, the K-band spectra suggested that Sedna's surface was highly processed by cosmic rays, having been isolated in a deep freeze for eons. Sedna's bland spectroscopic profile and deep red, dark albedo stand in stark contrast when compared to Pluto's spectrum (which shows deep methane absorption),



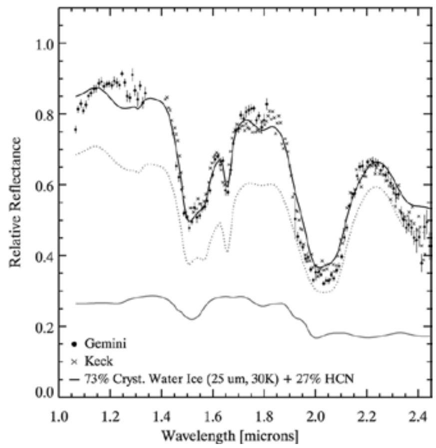


Figure 3 (above left): Reflectance near-infrared spectra of 2003 UB313 (Eris) from Gemini North. Pluto and Eris show very similar properties at this scale.

Figure 4 (above center): Composite spectrum of 2003 EL61 (Haumea) showing that a predominantly crystalline water-ice model fits the major features of the spectrum.

Figure 5 (above right): Gemini North (GMOS) image of Asteroid 118401. This new comet is centered in the frame with the tail of the comet clearly seen as the v-shaped fan of emission extending from the object to the left.

and that of its moon Charon (with deep water-ice absorption). Sedna's spectrum is also very unlike those of other distant worlds that have since been revealed when a spate of discoveries in the mid-2000s significantly expanded the number and diversity of known outer solar system bodies.

For instance, the Gemini infrared K-band spectrum of another dwarf planet (that would ultimately become known as Orcus) was paired with that from Sedna in a 2005 paper by C. Trujillo et al. Where Sedna's spectrum was featureless, Orcus' displayed strong water absorption features. These hinted that Orcus' orbit, which brings it much closer to the Sun than Sedna, making its surface more dynamic, promotes surface renewal. Such resurfacing is also thought to be responsible for features on Pluto and Charon (Figure 2, previous page). A paper by Jason Cook et al. explains how his team used NIRI adaptive optics (AO) spectroscopy to study Pluto's moon Charon and found evidence for significant surface renewal and freshly crystallized water ice with ammonia hydrates on its surface. All of this points to the possible existence of very dynamic internal processes that impact surface characteristics, as well as the spectra, of these frozen worlds beyond Neptune.

The conclusion that these cold, isolated worlds are more dynamic than first expected is further supported in rather dramatic fashion by Gemini observations of Eris (the largest dwarf planet known, and the object that ultimately "dethroned" Pluto) and the extreme dwarf planet, Haumea (which, like Eris has its own moon, but is elongated, and has an exceptionally rapid rotational period). Both of these extremely compelling bodies came under the scrutiny of the Near-Infrared Imager and Spectrometer (NIRI) on Gemini North (Trujillo et al. and Brown et al.). These data reveal strong evidence for pure methane ice on Eris (see Figure 3) and crystalline water ice on Haumea (see Figure 4). Understanding these frozen worlds, which may bridge the Oort Cloud and Kuiper Belt, brings us to another well-known class of icy solar system objects: comets.

Comets have long been suspected of supplying the early Earth with a source of water and other compounds (that might even include organic molecules). But the evidence linking comets to the origin of water in Earth's ancient history has been, in many cases, circumstantial. The comet/water connection got a boost by Gemini observations in 2005, when University of Hawai'i astronomers Henry Hsieh and David Jewitt discovered a new class of comets originating from within the asteroid belt. High spatial resolution optical images with the Gemini Multi-Object Spectrograph (GMOS) of Asteroid 118401 verified that it was ejecting dust like a comet (see Figure 5). This led to the conclusion that Asteroid 118401 and several other similar bodies also studied by the team represent a new class of comets; these bodies, they argue, could have delivered a significant amount of water to the young Earth, which is thought to have originally formed hot and dry.

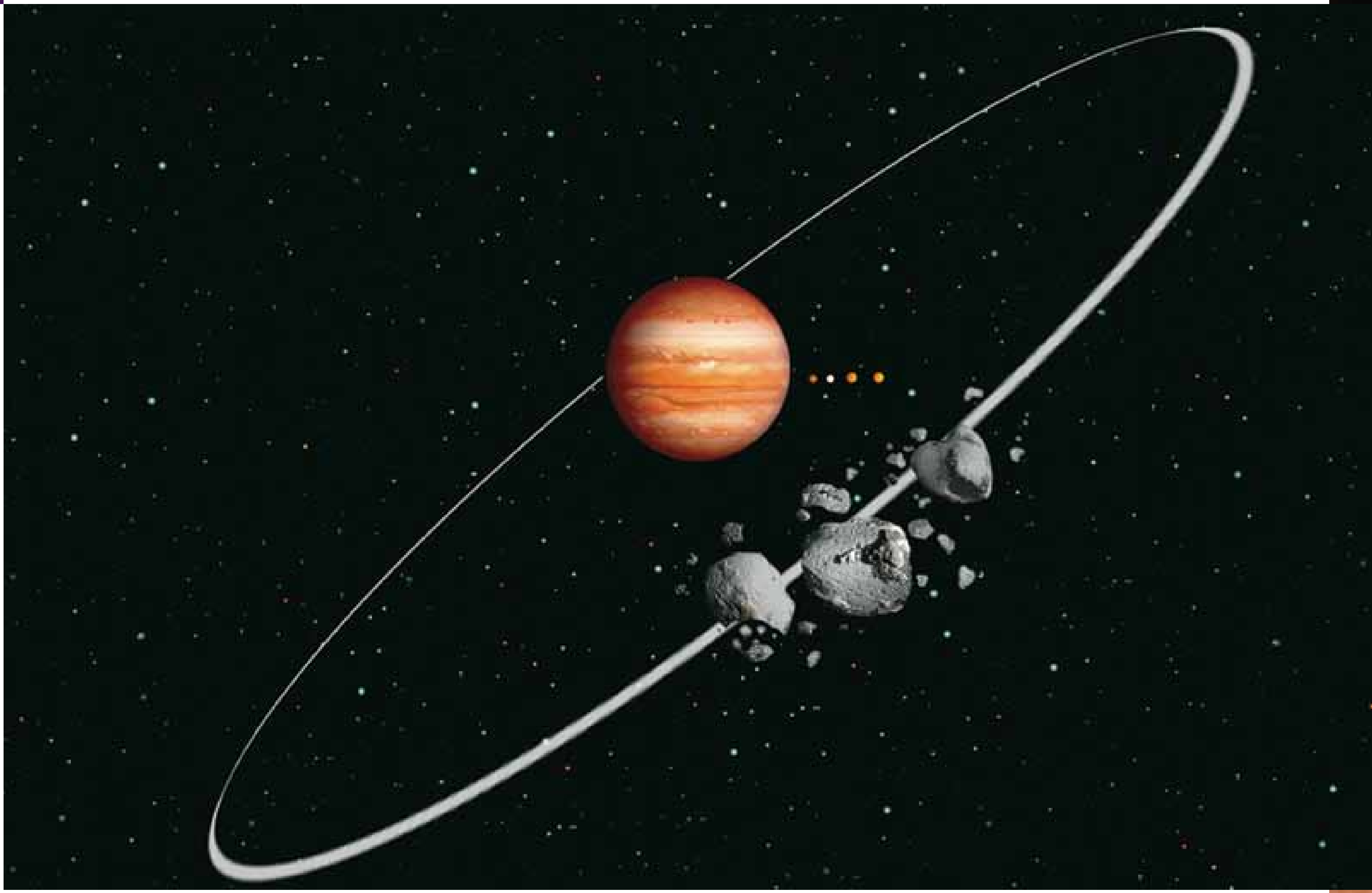


Figure 7 (above): Artist's rendering of irregular satellites around Jupiter after a collision. Jupiter's four large moons are shown for orbital scale. Gemini artwork by Jon Lomberg

Likely related to the asteroids is a class of irregular satellites: outer planet moons with odd orbits. These maverick bodies often display highly elliptical orbits —and can travel in any direction, at odd inclinations. It is thought that these oddball moons (see Figure 7) were captured by the gas giant planets from parent bodies in the asteroid belt. These asteroidal bodies broke up and formed families of objects that have similar spectral characteristics. In February 2003, a team led by Tommy Grav (Harvard) used NIRI to obtain near-infrared photometry to characterize the infrared colors of many irregular satellites around Jupiter and Saturn. What they found confirmed that these objects were indeed identical in color to asteroids in the outer part of the main asteroid belt. This result continues to demonstrate how the minor bodies of our solar system are more dynamic, diverse, and in some cases even more deviant than anyone had ever imagined.

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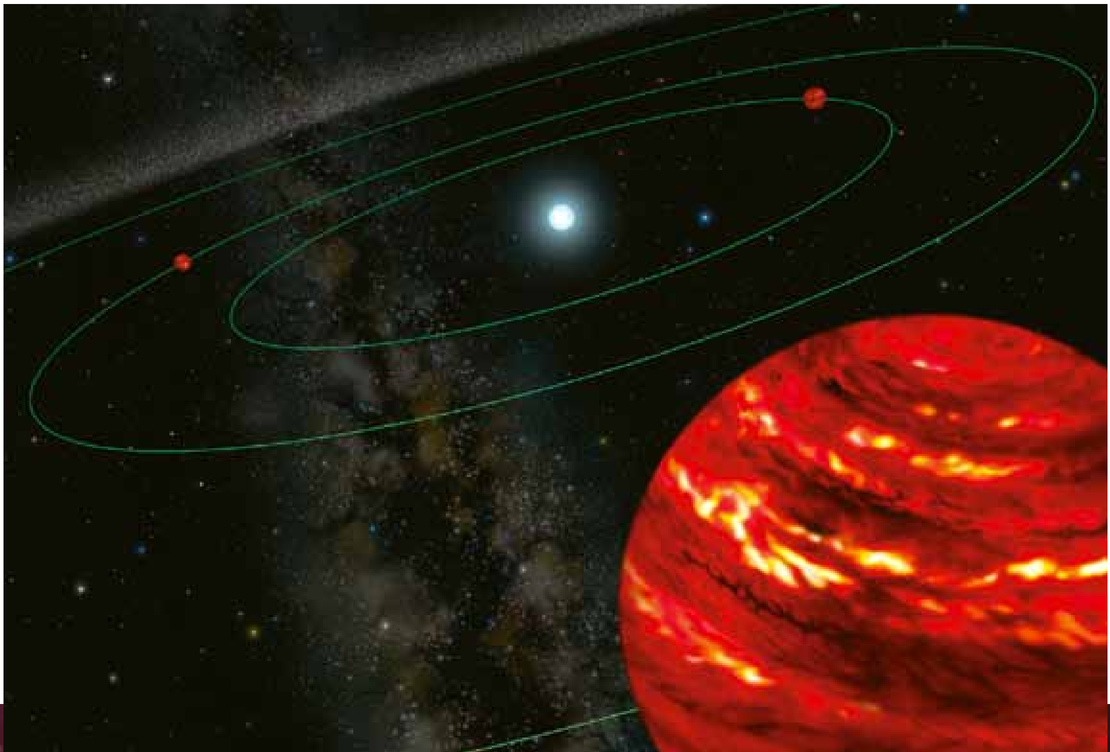
Direct Imaging & Spectroscopy of Exoplanets

Considering Gemini's exquisite spatial resolution and infrared sensitivity, it's no surprise that the study of exoplanets and low-mass objects has emerged as one of the most requested and productive applications demanded by our users. The result is a plethora of "firsts" and highly cited papers based on Gemini data. Furthermore, ongoing and future projects, like the Gemini NICI Planet-Finding Campaign and much-anticipated Gemini Planet Imager (GPI) instrument, portend an extremely bright future for Gemini in the area of exoplanet research.

Until very recently, most planet discoveries were made using radial velocity techniques (using high-resolution spectroscopy), which tend to favor the discovery of giant planets orbiting rather close to their host stars. Because key Gemini strengths lie in high-resolution adaptive optics (AO) in the near-infrared (and low- to medium-resolution spectroscopy), the direct imaging and spectroscopic studies of worlds orbiting farther away from their host stars is causing the emergence of a whole new class of exoplanets—and Gemini is leading the way in the search.

Gemini's impact in the field of exoplanet research began ramping up in December 2007, with a paper in *The Astrophysical Journal* on the Gemini Deep Planet Survey (GDPS) led by René Doyon of the Université de Montreal

Figure 1: Artist's conception of the HR 8799 planetary system. Gemini artwork by Lynette Cook



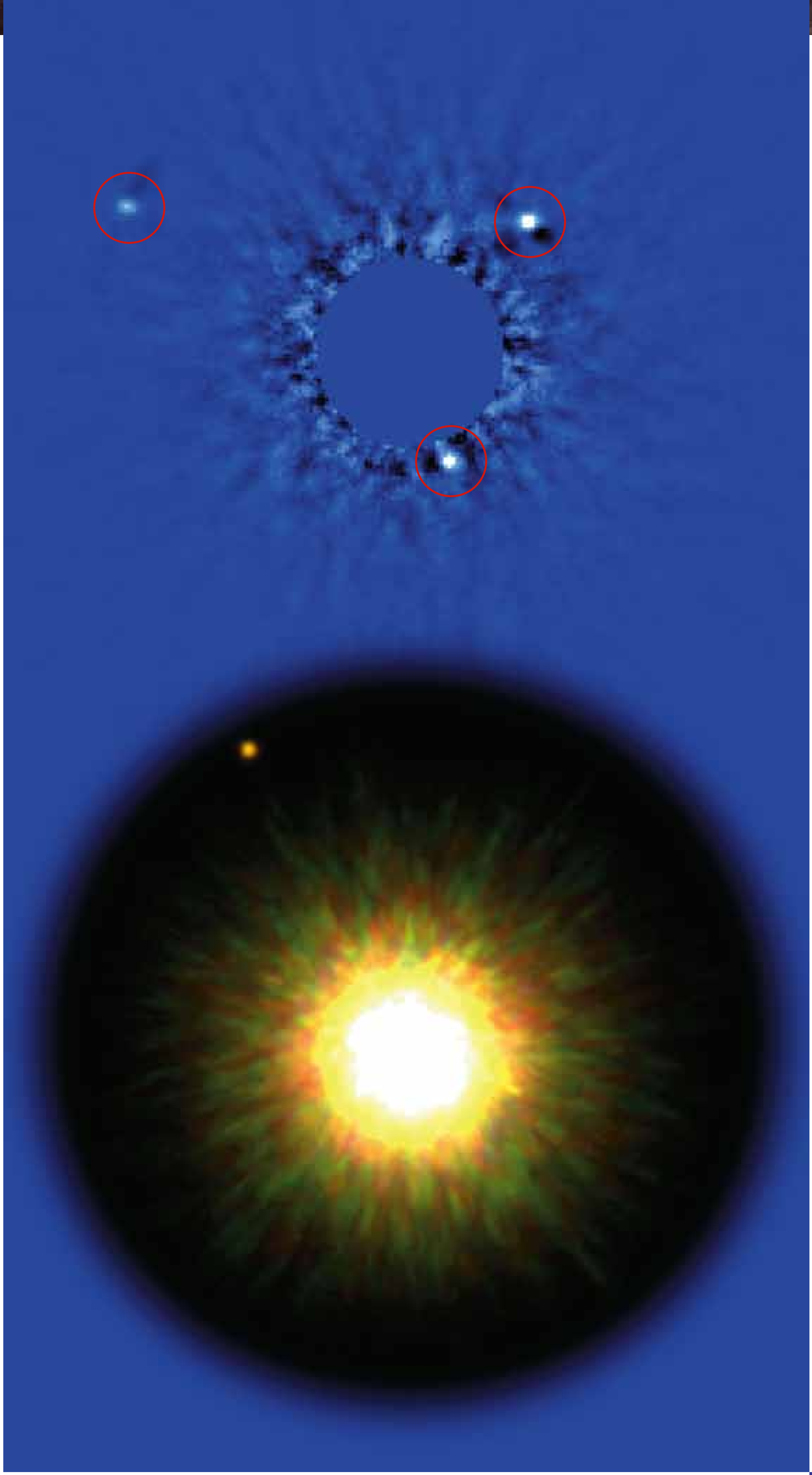
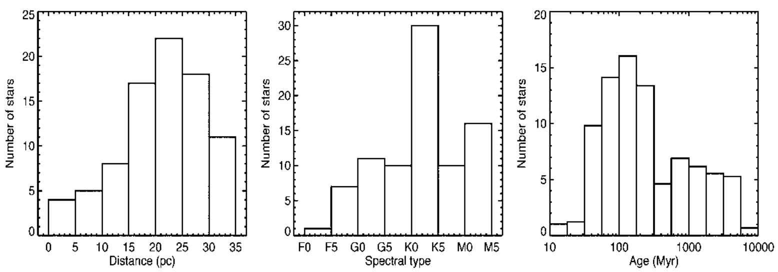


Figure 2 (top): K-band (2.2 microns) AO image of the HR 8799 planetary system acquired on September 5, 2008 (north is up and east is left). The three planets are designated with red circles. The stellar flux has been subtracted using ADI (see page 19 for details) and the central saturated region is masked out. Multi-epoch observations have shown counterclockwise Keplerian orbital motion for all three planets.

(bottom), Gemini image of 1RXS J160929.1-210524 and its likely ~8 Jupiter-mass companion (at about the 11:00 position. This image is a composite of J-, H- and K-band near-infrared images. All images obtained with the Gemini Altair adaptive optics system and the Near-Infrared Imager (NIRI) on the Gemini North telescope.



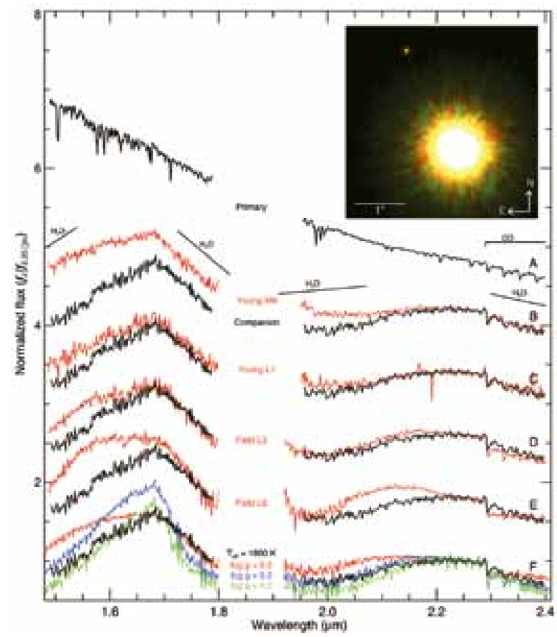


Figure 3 (above left): Distance, spectral type, and age of stars observed in the Gemini Deep Planet Survey.

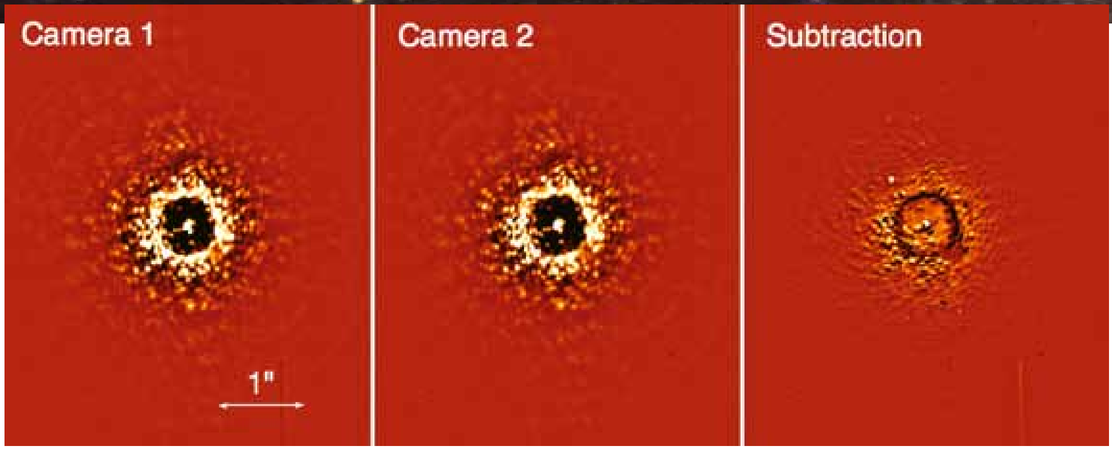
Figure 4 (above right): Near-infrared spectra of 1RXS J160929.1-210524 and its candidate companion. The primary's spectrum (row A) is as expected for a temperature of about 4000 K (spectral type K7). The candidate companion's spectrum (black curves repeated in rows B--F) is compared with the spectra of two young brown dwarfs (red curves on rows B--C; spectral types M9 and L1) and two older, cooler brown dwarfs (red curves on rows D–E; L3 and L6. The "triangular'" hape of the left part of the companion's spectrum is in much better agreement with the two young brown dwarfs, indicating the candidate companion has low gravity. In turn, this implies it has not yet fully contracted and is still young.

and David Lafrenière of the University of Toronto. This survey of 85 candidate stars used the Near-Infrared Imager and spectrometer (NIRI) with the Altair adaptive optics (AO) system on Gemini North and found no new planets by direct imaging. Given the selection criteria for the sample (see figure 3), a statistical analysis of these data indicate that the 95 percent credible upper limit—for the fraction of stars harboring at least one planet more massive than two Jupiter masses with a semi-major orbital axis in the range of 25-420 astronomical units (AU) or 50-295 AU—is 0.23 or 0.12, respectively. These upper limits, the most precise ever obtained, leave little room for the existence of a swarm of giant exoplanets orbiting their stars at distances greater than the size of our own solar system. The boundaries set by this study continue to be highly cited in the exoplanet research community.

In 2008, a team headed by David Lafrenière announced that their group discovered the first likely true planet by direct imaging using Gemini. The image and spectrum, made using the Altair AO system with NIRI on Gemini North, still required proper-motion studies to confirm the object's association with the star 1RXS J160929.1-210524. However, the potential planet's spectroscopic signature made it an extremely strong candidate. Located some 500 light-years away, the likely planet lies some 330 AU from its host star. The object's spectrum also suggests a surface temperature around 1800 K and a low surface gravity, indicative of something that is very young and still hot. As this issue goes to press, Lafrenière is producing a paper presenting evidence that the star and planet share mutual proper motion. Once published, this paper is expected to verify the original tentative conclusion of a true direct-imaging exoplanet discovery.

Only a few months after the Lafrenière announcement, an international team led by Christian Marois of the National Research Council of Canada's Herzberg Institute of Astrophysics, presented what could only be described as an exoplanet "hat trick." This time, instead of finding only one world orbiting its host star, Marois et al. discovered three (see Figures 1 and 2, previous page). The Gemini Altair/NIRI data, augmented by archival data from the W.M. Keck Observatory, resulted in the quick realization that this planetary "first family" was indeed the first confirmed direct image of a planetary system orbiting a normal star outside of our own neighborhood. The star, called HR 8799, is about 130 light-years away and has a mass about 1.5 times that of our Sun. Its planets range from about 7 - 10 Jupiter masses, with distances spanning 25 - 70 AU from the host star. Team member Bruce Macintosh of the Lawrence Livermore National Laboratories said in the Gemini press release issued on November 13, 2008, "Until now, when astronomers discover new planets around a star, all we see are wiggly lines on a graph of the star's velocity or brightness. Now we have an actual picture showing the planets themselves, and that makes things very interesting."

Spectroscopy notwithstanding, and going beyond "wiggly lines on a graph," the combination of Gemini's AO spatial resolution and infrared sensitivity are complemented in the search for exoplanets by the application of powerful



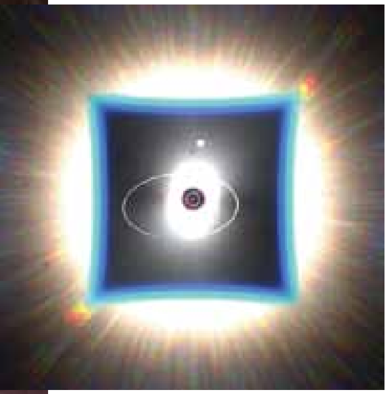


Figure 5 (top right): Speckle subtraction using NICI's dual-channel cameras. The left and center panels are images of the same star taken at the same time at slightly different wavelengths. The difference between the two images is shown in the right panel. The darker circle in the center is due to the coronagraph (which allows about one percent of the starlight through so the precise location of the star can be determined).

Figure 6 (above): Simulated GPI color composite H-band image of a 1h long integration on a 75 Myr G2V star at 20pc. The white object North of the star is a background object (no methane) while the object located South and East is a 4 M_{Jup} planet (with methane, its orbit is also drawn).
Image by C. Marois

techniques like angular differential imaging (ADI). ADI's power comes from the fact that, during a prolonged observation, the telescope's field of view rotates, and any systemic optical aberrations (speckles) appear to drift relative to the astronomical target. The aberrations can then be isolated and subtracted out to reduce noise in the final data sets. While not unique to Gemini, ADI is fully integrated into our observational and data-reduction procedures, giving our user community an extremely powerful suite of tools for finding faint point sources very close to what are often bright primary stars.

More recently, the full integration of the Gemini Near-Infrared Coronagraphic Imager (NICI) at Gemini South adds a curvature-based AO system, with a coronagraphic occulting mask to provide even better signal to noise and enhanced contrast between potential planets and their bright host stars. This combination of technologies and techniques power the Gemini NICI Planet-Finding Campaign led by Michael Liu of the University of Hawai'i. This systematic search of about 300 potential host stars is currently in its second epoch of observations and represents the single largest campaign science program ever performed at Gemini.

Looking toward the immediate future, the Gemini Planet Imager (GPI) is a next-generation instrument scheduled for delivery and integration at Gemini South in 2011-12. GPI brings integration of advanced AO correction, coronagraphic masks, spectroscopy, polarimetry, and diffraction-limited images between 0.9 to 2.4 microns into one cohesive package.

The current Gemini instruments for exoplanet research have already established a legacy that is propelling us into the next decade of science. The tools that allow our users to explore other worlds will undoubtedly continue to be in high demand for the foreseeable future, as will the next-generation of instruments. For the next 10 years, our users will be asking challenging questions about exoplanets at the same time they are pushing our technology to the limit. This combination will determine the impact of exoplanet observations on our research communities and on society at large.

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Bridging the Gap Between Planets & Stars

In the mass continuum of stellar objects, the most massive O-type stars define one extreme; while rare, their masses can exceed 100 times that of our Sun. At the other extreme are the brown dwarfs, where the boundary between stars and planets becomes fuzzy; here, masses are typically measured in multiples of Jupiter's mass. In this latter realm, it's not uncommon for a brown dwarf to have a mass only a few percent that of the Sun. Like the study of exoplanets, whose masses are similar to those of many brown dwarfs, examining these low-mass specimens requires extreme sensitivity at longer wavelengths, as their temperatures and luminosities plummet when compared to those of more massive stars (brown dwarfs are typically cooler than 2000 K). Gemini's optimization in the infrared, spatial resolution, and 8-meter aperture, make it an obvious choice for studying the dim, warm glow of these low-mass objects.

The study of low-mass objects has presented astronomers with a wide range of surprising results, where odd combinations of partners are often the norm rather than the exception. This was true right from the start at Gemini when, in 2002, a team led by Michael Liu (University of Hawai'i) used the Hokupa'a adaptive optics system on Gemini North and the W.M. Keck Observatory to observe a nearby, almost middle-aged Sun-like star known as 15 Sagittae. To Liu's surprise, his team found a brown dwarf, with a mass between 55-78 times that of Jupiter, in a relatively close orbit (about 14 astronomical units (AU)) from the primary star. The processed Gemini image is shown in Figure 1.

Less than a year later, Laird Close (University of Arizona) announced the results of a Gemini survey in which his team found a low-mass pair consisting of a L-type brown dwarf in a tight orbit with the M-type star LHS 2397a (see Figure 2).

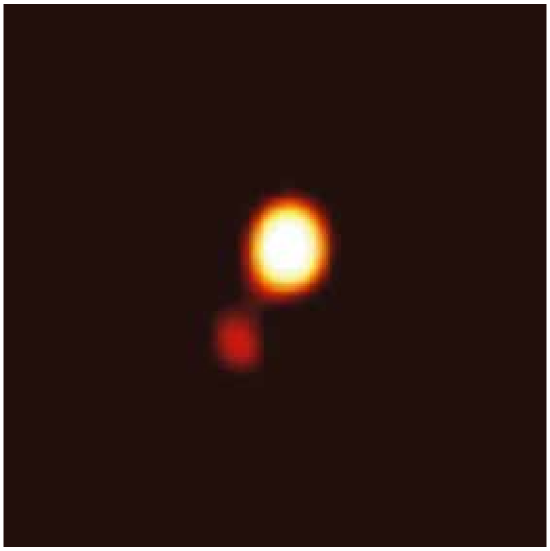

Figure 1 (left): Processed image of brown dwarf around 15 Sagittae that was revealed for the first time by Gemini.

Figure 2 (right): Image of LHS 2397a obtained on February 7, 2002, at Gemini North.

Both images (Figures 1&2) used the University of Hawaii's adaptive optics system Hokupa'a and the QUIRC infrared imager.

Figure 3: Artist's conception of the Epsilon Indi system showing Epsilon Indi and its brown-dwarf binary companions. Due to the perspective of the brown dwarf companions, the relative sizes are not represented in this illustration. Gemini artwork by Jon Lomberg

In this case, the dwarf, with a mass about 38-70 times that of Jupiter, is only about three times the Earth - Sun distance from its primary. What really surprised the researchers, however, is how many low-mass pairs they found in the survey. Previously, most very low-mass stars and brown dwarfs were thought to be solo objects wandering though space after being expelled from their gas-cloud nurseries during the formation process. Now Close believes that "nature does not discriminate against low-mass stars when it comes to making tight binary pairs." Although rarer than higher-mass binaries, there are still more low-mass binaries than can be accounted for by our current understanding of star formation and much work needs to be done to explain this excess.

The pace of brown dwarf discovery at Gemini continued at a fever pitch in 2003, when a nearby neighbor, Epsilon Indi B, was imaged by PHOENIX and GMOS (without adaptive optics) at Gemini South (see Figures 3 & 4). As a brown-dwarf companion to the primary star Epsilon Indi (a fifth-magnitude star in the southern constellation Indus), Epsilon Indi B was concealing an even lower mass companion of its own, now known as Epsilon Indi Bb.

Gordon Walker (University of British Columbia, Vancouver, Canada) led the research team (although former Gemini astronomer Kevin Volk made the discovery) and commented, "In astronomy, the more we can study in detail, the more enlightening the results. To find a fainter brown dwarf companion hiding beside the brighter one, Epsilon Bb, opened up an important new direction in brown dwarf and exo-planet research."

Following the rapid announcement of this discovery in IAU *Circular* 8188, the competitiveness, as well as the rapidity of discovery in this field, became obvious when scientists using the Very Large Telescope (VLT) announced that they also

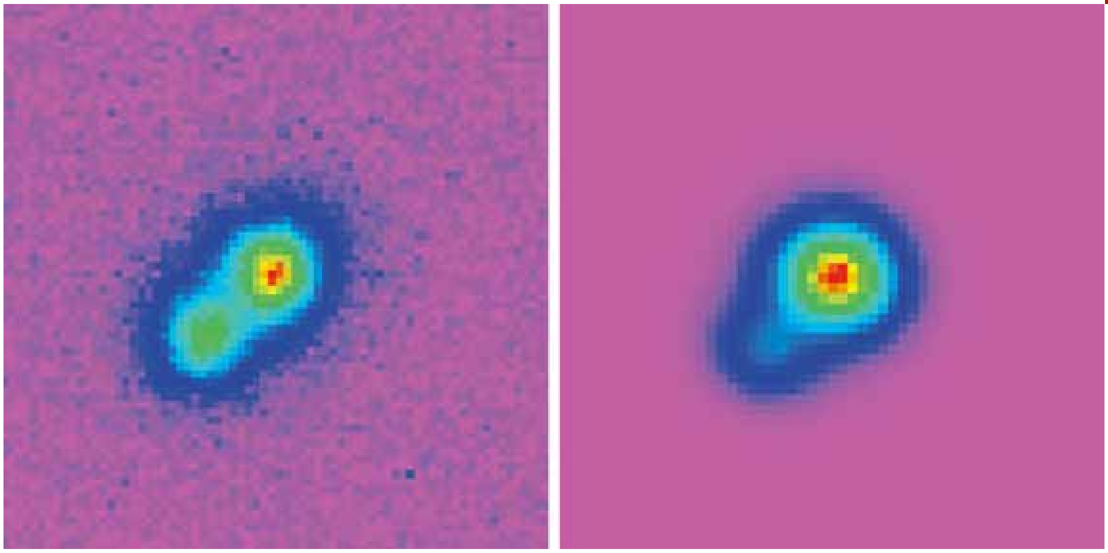

Figure 4: (left), Original Gemini South detection image of Epsilon Indi B/Bb obtained on August 18, 2003 ,with PHOENIX using a narrow-band filter within the J-band. (right), Gemini South Multi-Object Spectrograph (GMOS-S) z-band image obtained on September 2, 2003. Both images are 4 x 4 arcseconds across and were obtained without adaptive optics.

observed this new object, but saw it five days earlier using adaptive optics. The history of science is rife with similar stories which, almost without exception, happen in fields where research is vigorous and competitive.

Despite the intense competition, this was just the tip of a proverbial iceberg. The field of brown dwarf research, already active at Gemini and other observatories, was about to accelerate to a new level. A new survey called the United Kingdom Infrared Telescope (UKIRT) Infrared Deep Sky Survey (UKIDSS) propelled research by providing astronomers with a plethora of new targets. In this field, records would continue to be broken almost as quickly as they could be set.

One such example was featured at the May 2007 meeting of the American Astronomical Society in Honolulu, Hawai'i, when a Gemini South GNIRS near-infrared spectrum of the ultra-low-mass object ULAS J0034-00 (discovered as part of UKIDSS, S. Warren et al.) became public. The Gemini spectrum (see Figure 5) convincingly showed that the 15-30 Jupiter-mass body had a surface temperature of only 600-700 K, making it the coolest solitary brown dwarf known (at the time) and further closing the temperature and mass difference between stars and planets.

Only a month prior to the ULAS J0034-00 announcement, Gemini science fellow Étienne Artigau (now at Université de Montréal) spearheaded the discovery of a low-mass binary pair separated by the extraordinary distance of over 5,000 times the Earth-Sun distance. The pair, believed to be less than 100 Jupiter masses each, would, if scaled to the size of baseballs, be an unimaginable 200 miles apart, yet still gravitationally connected. How this pair maintains its extreme distance relationship without being diverted apart remains a mystery. This pair, estimated to be about a billion years old and have temperatures of about 2,200 degrees Celsius, has been followed up with GMOS observations confirming its age.

While much has been learned by the spectroscopic follow-up of low-mass-object surveys and finding the smallest and coolest specimens, a diverse multi-wavelength approach can tell us even more. This is exactly the path that Edo Berger (Princeton University, now at Harvard University) et al. followed in 2007-2008 by combining simultaneous GMOS optical spectroscopy data from Gemini (see Figure 6), radio data from the Very Large Array, X-ray data from *Chandra*, and ultraviolet data from the *Swift* satellite. His team did this with several late-M and L dwarfs in order to sample the chromospheres and coronae of ultra-cool dwarfs and better understand what influence, if any, magnetism has around these stars. Brown dwarfs have long been thought to be relatively inactive magnetically. But there was some evidence that hinted at magnetic activity in late M-type stars. So the question remained: is there magnetic activity in even cooler objects? To the surprise of the team, the multi-wavelength observations showed that magnetism does indeed play a significant role in sub-stellar objects, and that the magnetic field structures appear to be large-scale dipoles with an unexpected strength of several kilo-Gauss.

Most recently, in 2009, Ben Burningham (University of Hertfordshire) discovered an extremely cool companion to the red dwarf Wolf 940. Follow-up spectroscopic observations with NIRI on Gemini North (see Figure 8) indicate that this newly

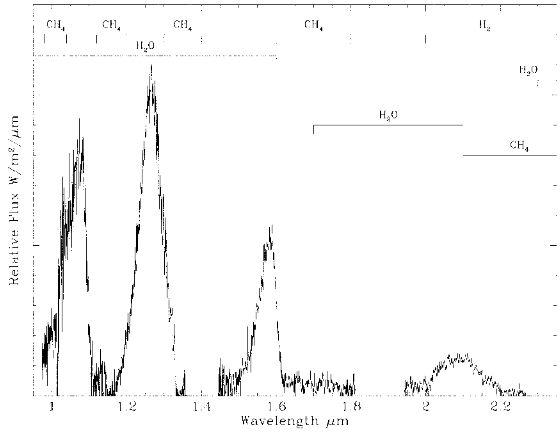

Figure 5: (upper left), Gemini South GNIRS spectrum of ULAS J0034-00.

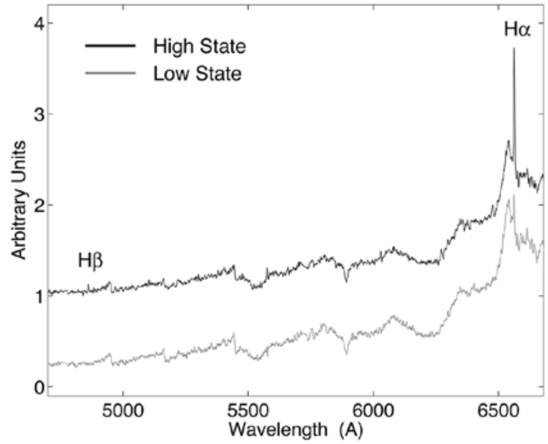

Figure 6: (upper right), Sample Gemini North GMOS optical spectra of TVLM513-46546 in the high and low Balmer emission-line states. The high-state spectrum has been offset upward for clarity. This object was part of the work by Berger et al. to look for magnetism around low-mass objects.

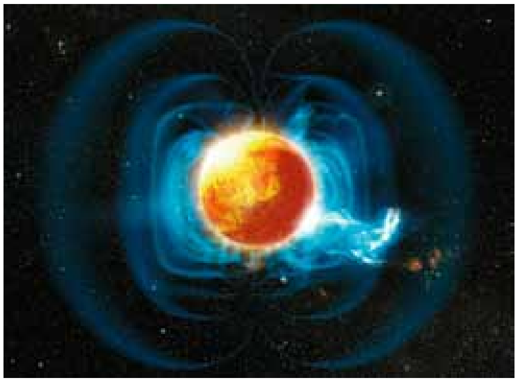

Figure 7: (lower left), Artist's rendition of what the magnetic fields and surface might look like on TVLM513-46546. Note that the hot-spot that is estimated to cover up to 50 percent of the surface area of the object is oriented to the left and is not entirely visible in this orientation. Gemini Observatory artwork by Dana Berry, SkyWorks Digital Animation.

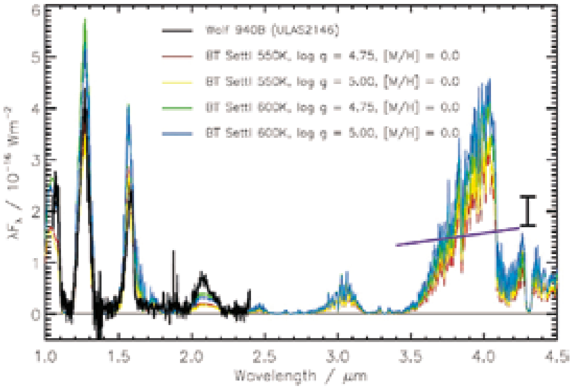

Figure 8: (lower right), NIRI spectrum (black line) compared to models of a cool brown dwarf atmosphere with different temperatures and effective gravities. In addition to the JHK spectroscopy, L-band photometry (with error bar) from NIRI of Wolf 940b is shown as the dark blue line between 3.4 – 4.2 microns

discovered companion (Wolf 940b) has a spectral type of T 8.5 and a temperature of only about 570 K, making it amongst the coolest known objects beyond our solar system and (currently) the coolest brown dwarf stellar companion.

All of this leads to two conclusions: 1) There are plenty of discoveries yet to be made in the study of dwarf bodies; and, 2) Gemini will continue to be at the forefront when it comes to analyzing the faint glow of these small, cool stellar wannabes.

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Young Stars & Dusty Disks

Unraveling the sequence of events that results in the birth of stars, and in many cases planetary systems, is not just important for astronomy, but also for giving humanity a sense of its place in the cosmos. Fortunately, there is no shortage of interesting nearby examples to study, and the thermal-infrared optimization of Gemini's telescopes makes them uniquely suited to excel in this area of astronomical research.

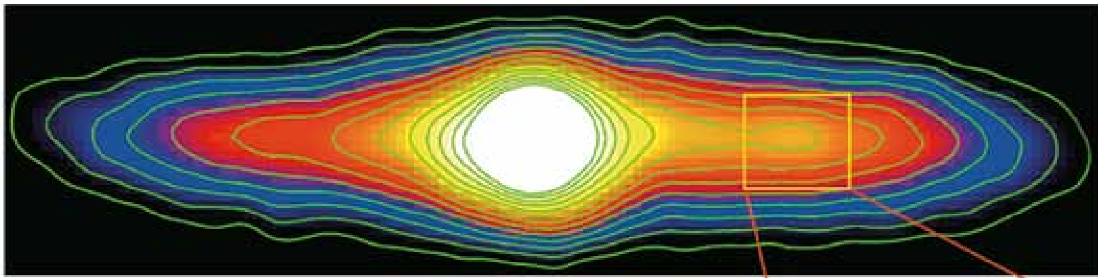
The mysterious early stages of stellar birth are often shrouded and obscured by dense clouds of optically thick gas and dust. However, infrared observations have penetrated many of these murky and chaotic realms to reveal young bodies with accretion disks and jet-like outflows, (see the article on the birth of a very massive star by Ben Davies starting on page 74 of this issue). Occasionally, these objects display short-lived transient flare-ups, such as in 2003 when American amateur astronomer Jay McNeil noticed a newly glowing cloud in the constellation of Orion. Named after its discoverer, the McNeil Nebula is home to a pre-natal star that suddenly shone forth like a lighthouse beam through a temporary breach in the dense clouds surrounding its stellar nursery. Rapid follow-up observations at Gemini allowed University of Hawai'i astronomers Colin Aspin and Bo Reipurth to study the event and watch it unfold over several months (see Figure 1). The quick turn-around of the observations was made possible in large part by the flexibility of the queue-scheduling scheme which Gemini was just initiating at the time of this event.

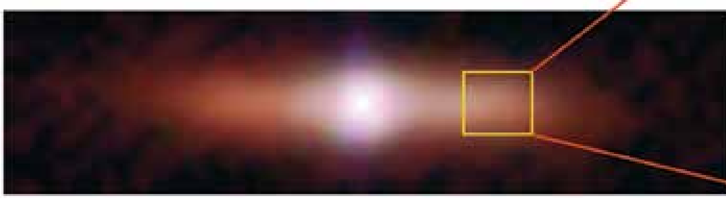
Figure 1: Gemini Multi-Object Spectrograph (GMOS) image of the McNeil Nebula obtained on February 14, 2003 with Gemini North.

Fortunately, detecting the formation of possible planetary systems around other stars is less time-critical than an event like the sudden illumination of McNeil's Nebula. In the more advanced stages of planet formation, young stars have flattened disks of dust and gas around them. These particles are the likely building blocks of planets. Observations of these circumstellar disks in the thermal infrared are key to understanding their diverse characteristics.

Gemini's foray into the study of proto-planetary circumstellar disks began in late 2001 – during what might, in retrospect, be considered the commissioning of the Gemini South telescope system – and involved the early use of the mid-infrared instrument OSCIR on the Gemini South telescope. These first observations focused on the infrared excess around the bright star Beta Pictoris (originally discovered in 1983 by the *Infrared Astronomy Satellite*, or *IRAS*) and hinted at an intriguing edge-on disk full of potentially interesting structure.

Figure 2 : Artist's rendering of what the environment around HD 23514 might look like as two Earth-sized bodies collide. Artwork by Lynette Cook for Gemini Observatory.





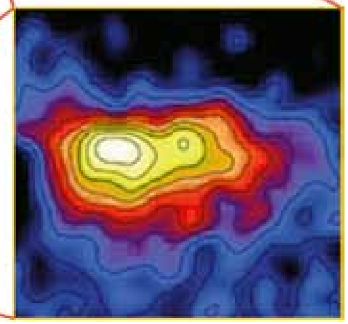


Figure 3: (top), Mid-infrared image of the β Pictoris disk as obtained with T-ReCS on Gemini South at 18.3 microns. Differences in the shape and strength of dust emission within the disk can be seen as the observed wavelength changes. Note: The clump where the suspected collision occurred is at a distance of about 52 AU and is expanded below in Figure 4.

Figure 4: (bottom left), Color composite of disk using T-ReCS data at 8.7, 11.7, 12.3, 18.3 and 24.3 microns.

Figure 5: (bottom right), Detail of emission in SW wing at 18.3 microns. This tightly confined excess emission is likely the result of a recent collision between two large planetesimals.

However, because of signal-to-noise issues, the observations required follow-up confirmation that finally came with the use of T-ReCS on Gemini South in 2003-4. The new data (see Figures 3 - 5), verified some of what OSCIR had detected in 2001 and was published in the journal *Nature* (C. Telesco et al.). The result was also presented at a press conference during the January 2005 meeting of the American Astronomical Society in San Diego, California.

Like other circumstellar disk results to follow, this early evidence led to the conclusion that very recent catastrophic collisions of bodies within Beta Pictoris' rocky, dusty disk created a debris cloud of small dust particles that gave the disk a lopsided appearance at specific mid-infrared wavelengths (see Figure 4). Models predict that the wind from the central star clears away such small particles (about the size of cigarette smoke particles) relatively quickly, if they are not being continually replaced by ongoing, frequent collisions.

A similar conclusion was announced later in 2005, when another *Nature* paper spotlighted the work of Inseok Song and his collaborators. The star, BD +20 307, was another *IRAS* infrared excess target, but this time the team (with both Gemini and Keck data) used spectroscopy to determine the temperature and particle size of the infrared-emitting dust as well as pinpoint the distance of the dust-producing collisions from the star. From this evidence, the team concluded that collisions between asteroids (or even Earth-sized planets) created the dust. Even more exciting, the collisions were occurring frequently at a distance from the Sun-like star comparable to the Earth-Sun distance in our solar system. For the first time, a solar-system analog existed that could be showing what our own solar system was doing during its formation (or during the era of heavy bombardment) some 4.5 billion years ago (see Figure 2).

In accord with the BD +20 307 result, a team led by Joseph Rhee (University of California, Los Angeles) et al. (that also included I. Song) found another dusty disk around a sun-like star (HD 23514) in the well-known Pleiades star cluster. In this case, the warm dust is also at a similar Earth-Sun distance, but the primary flux density peaks at a non-standard wavelength of ~ 9 microns (see Figure 7). The presence of so much small warm dust at this distance from the star is not easy to account for, unless a large amount of material is converted to very fine dust due to collisions in the first hundred million years of this sun-like star's life. The team concludes that the existence of dust near BD +20 307 and HD 23514 make it likely that such terrestrial planet formation is common.

Another compelling finding surrounds the star Zeta Leporis and Gemini South T-ReCS observations made by a team led by Margaret Moerchen (while a Ph.D. student at the University of Florida). Like BD +20 307 and HD 23514, Zeta Leporis is surrounded by dust of recent origin. However, the most intriguing part of this work is the detection and first-ever full-spatial resolution of what is likely an analog to the asteroid belt in our own solar system. At about the

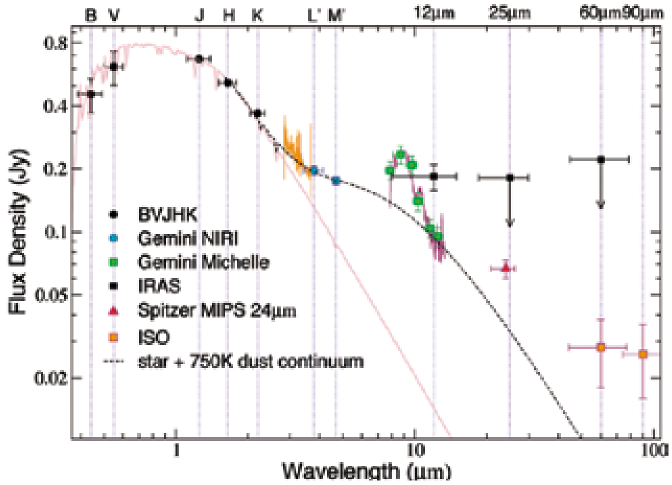


Figure 6 (above left): Zodiacal light as photographed from Mauna Kea shortly after the end of evening twilight. The wedge-shaped glow (whitish glow at center) is produced by the scattering of sunlight by the small amount of dust remaining from the formation of the solar system. In a system like those discussed in this article, the density of the dust is thought to be about one-million times greater than what currently exists in our solar system to create this glow.

Figure 7 (above right): Spectral energy distribution of the dusty 100-million-year-old solar-type star HD 23514 in the Pleiades star cluster.

same distance as the asteroid belt in our planetary system, Moerchen detected a maximum mid-infrared flux around Zeta Leporis and accurately measured its separation from the star. This infrared flux is indicative of many collisions between multiple small bodies in orbit around the star, just like one would expect in the formation of the asteroid belt.

Finally, at the other end of the stellar life cycle, a team led by UCLA astronomer Eric Becklin offers up a unique view of the dusty fate of old planetary systems and what our solar system might have in store for us in another 4-5 billion years. This time, using the MICHELLE mid-infrared spectrograph, Becklin's team looked at an ancient stellar ember, a white dwarf named GD 362 and found an unexpected preponderance of photospheric metals. According to Becklin, "This is not an easy one to explain. Our best guess is that something similar to an asteroid, or possibly even a planet around this long-dead star, is being ground up and pulverized to feed the star with dust. By studying the composition of the dust, we can actually determine the material in a far off planetary system."

Piecing together a coherent picture of the formation (and demise) of planetary systems from proto-planetary circumstellar debris disks is still a young field that will keep astronomers and theorists busy for the foreseeable future. Gemini's mid-infrared sensitivity, spatial resolution, and instrument suite are well-positioned to continue the momentum of the past 10 years in this important area of study. Ultimately, our findings will allow us to assemble an understanding of our origins, just as clouds of gas and dust coalesced some five billion years ago to assemble the fortunate circumstances in which we can even ponder such profound questions.

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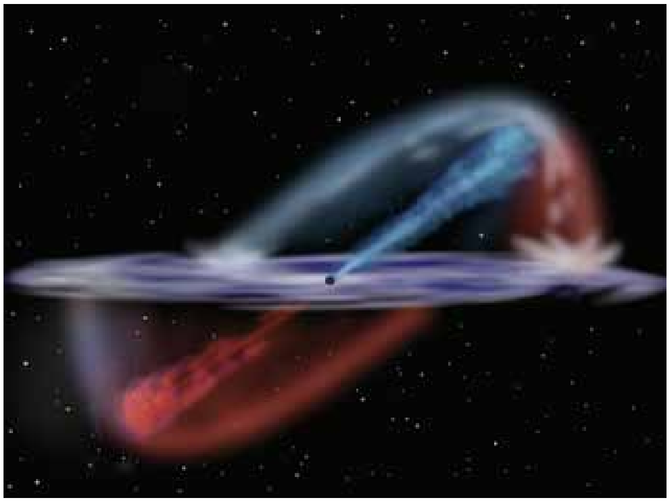
Active Galactic Nuclei



Studying the cores of galaxies is a diverse and dynamic field covering a wide range of energies and cosmological ages. In 2000, Gemini's first release of data on the core region of our Milky Way (see page 6) gave us a glimpse into the quiescent end of the galactic-core energy continuum. However, in galaxies where central supermassive black holes are on a feeding frenzy, the environment is a violent, energetic caldron of activity. These active galactic nuclei (AGN) are laboratories for high-energy astrophysics and an area where Gemini's capabilities, especially in the infrared and using high spatial resolution integral field spectroscopy, provide a window into the inner workings of AGN. Over the past decade, astronomers using Gemini have been treated to some of the highest-resolution, multi-dimensional views of AGN available. These views capture the voracious eating habits and dynamics of supermassive black holes that can grow to several billions of times the mass of our Sun.

Figure 1: Artist's rendition of the central region around NGC 1068, as seen from the edge of the disk that surrounds the core's black hole. The red- and blue-shifted radiation formed by the interaction between the disk and the bowshock at the end of the jets can be seen above and below the disk. Blue-shifted light is moving toward us and red-shifted light is receding.
Gemini artwork by Jon Lomberg

Integral field spectroscopy has been available at Gemini since nearly the beginning of science operations, when the Gemini Multi-Object Spectrograph (GMOS) became available on Mauna Kea in 2001. One of the first integral field spectroscopic observations (during science verification of GMOS) was led by Gemini astronomer Bryan Miller, who focused on the core of the one of the closest active galaxies: NGC 1068. Parsing the galaxy's light via a fiber-optics bundle in the GMOS integral field unit (IFU, see Figure 3, page 30), the commissioning team spectroscopically dissected the core of the galaxy and assembled it into a "data-cube." By expanding the data cube and studying the velocity signatures in the spectra at each of the 8,137 points covering the galaxy's core, a multi-dimensional image emerged. The data from NGC 1068 revealed evidence for a galactic-scale jet that, according to Jean-René Roy (then Deputy Director of Gemini), allowed astronomers for the first time "…to clearly see the jet's expanding lobe as its hypersonic bow shock slams directly into the underlying gas disk of the galaxy. It's like a huge wave smashing onto a galactic shoreline," (Figure 1).

Located only 14.4 megaparsecs away, NGC 1068 is the most-studied AGN galaxy in the sky. Because AGN radiate over a wide range of energies—from radio to X-rays—a nearby specimen like NGC 1068 is a popular target for astronomers observing at all wavelengths. However, the GMOS IFU observations provided a truly unique glimpse into the inner workings and dynamics of an archetypical AGN. A key interpretation of this work was published in 2006 Joris Gerssen of the University of Durham (UK). Concurrent with this paper, R. E. Mason et al. (2006) published results on spatially resolved mid-infrared spectroscopy of NGC 1068 based on 10-micron spectroscopic data from

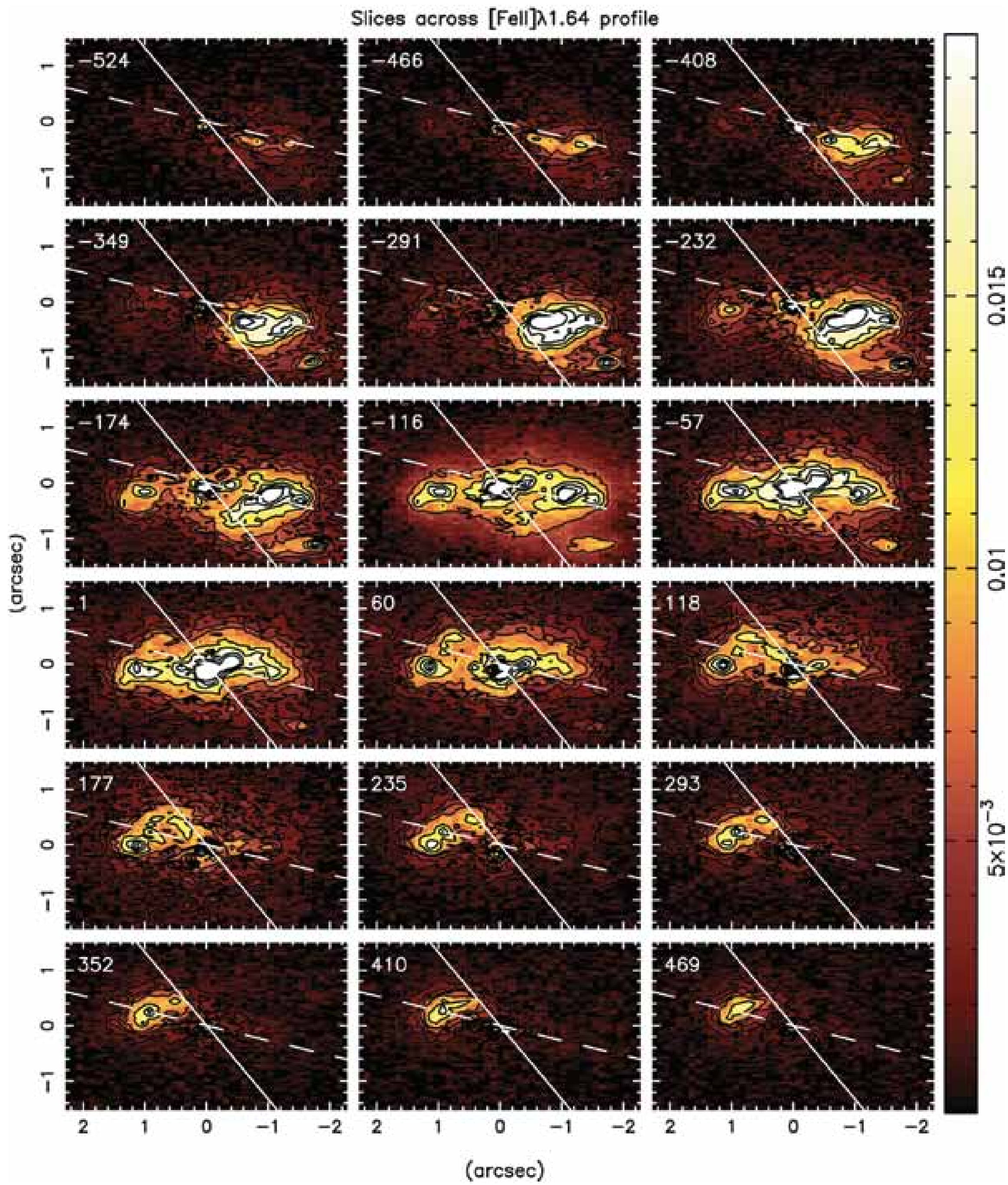


Figure 2: NIFS IFU channel maps of NGC 4151 along the emission-line profile of [FeII]λ1.64 microns, where each panel corresponds to a velocity bin centered on the value (in kilometers per second) shown in white in the left corner of each panel. The dashed and continuous lines are the axes of the bicone and major axis of the galaxy, respectively.

MICHELLE. These two papers assembled some of the most detailed optical and mid-infrared data ever obtained of this active galaxy's core. The studies revealed a complex emission-line morphology in the [OIII] doublet and hydrogen-beta lines (optical), striking variations in continuum slope, silicate feature profile and depth, and fine structure line fluxes on subarcsecond scales (mid-infrared). In the final analysis, the mid-infrared MICHELLE results give evidence for a compact source with a dusty torus obscuring the AGN, and AGN-heated silicate dust in the ionization cones. The variety of velocity components in the optical IFU optical data defy easy association with physical structures, but some appear to be associated with the expected biconical outflow. Other features hint at high-velocity flows or disk-like structures.

About six months prior to the GMOS IFU observations of NGC 1068, the visiting mid-infrared instrument OSCIR (University of Florida) on Gemini North provided what was the deepest mid-infrared images of M87's nucleus, which has the most well-known AGN jet and a central black hole estimated to "weigh in" at some three billion solar masses. The extended jet of M87 had never been imaged in the mid-infrared (see Figure 4, page 31) and the combination view of its nucleus and jet required a total of seven hours of telescope time (two hours on the jet, and five on the nucleus).

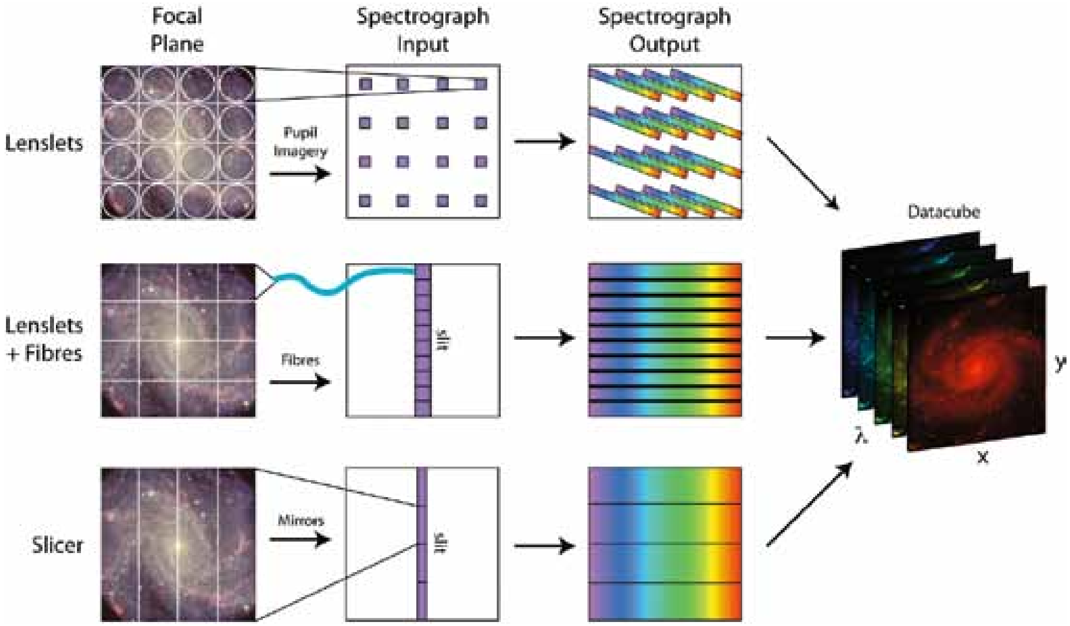


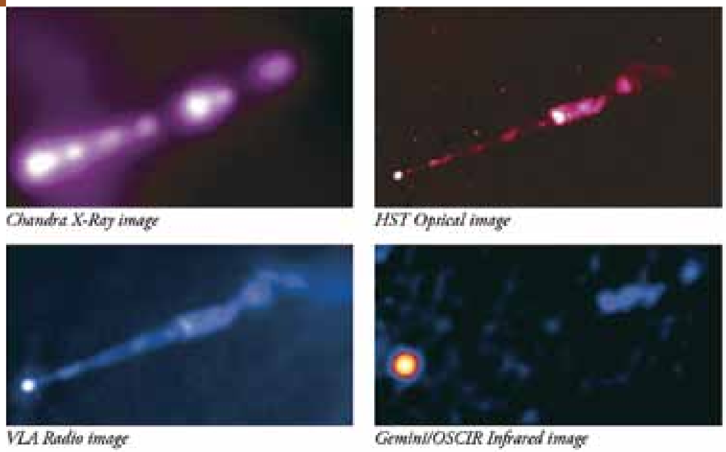
Figure 3: The main techniques for achieving integral field spectroscopy. Adapted from Allington- Smith, Content and Haynes (1998). The Lenslets and Fibres design in the central row is most similar to the GMOS IFU set-up. The Slicer design on the bottom row is most similar to NIFS's.

The results (Perlman et al., 2002) revealed that the theorized doughnut-shaped torus of material surrounding the black hole must contain far less material than other AGN tori, like those associated with Cygnus A or Centaurus A.

Indeed, in 2006 Gemini South observed the nucleus of Centaurus A with T-ReCS in the mid-infrared (J. Radomski), and, despite nearly diffraction-limited images, was unable to resolve the torus (confirming earlier Keck results that countered a tentative detection with the Magellan Telescope). Gemini's non-detection of an extended torus in M87 and Centaurus A deepened the concern that a "torus size crisis" was upon us; until astronomers could resolve a distinct torus in an AGN, we would likely never be able to understand the environment around the supermassive black holes that power these energetic behemoths. The findings sparked new (and tested existing) theoretical models of galactic tori to help settle the crisis. "These more recent models predict that, far from being a huge and uniform doughnut of gas and dust as once thought, instead the torus orbits the supermassive black hole in clumps. The size constraints placed by the Keck and Gemini data indicate that the clumps are primarily 'bunched up' and must orbit within a few light-years of the black hole," explained team member Nancy Levenson, who was then at the University of Kentucky and now serves as Gemini's Deputy Director and Head of Science.

T-ReCS observations of the Circinus galaxy, presented at the first Gemini Science Meeting in Brazil in 2005 by Chris Packham, put an early tight constraint on the torus size (see Figure 5). This partly led to the spectral energy distribution (SED) modeling, and indicated (even ahead of the 1068 observations) that the torus was indeed very small. To further address the challenges of modeling the unresolved AGN tori, and understand the environment around the black hole engines that energize AGN, Ramos Almeida partnered with Levenson, and Chris Packham (part of the T-ReCS team from the University of Florida), in assembling subarcsecond mid-infrared data (predominantly from Gemini North and South) to construct SEDs from 18 nearby Seyfert galaxies. Key to this science was the high spatial resolution (~0.3 arcsecond at 10 microns) which kept the data relatively uncontaminated by starlight and hence dominated by AGN/torus emission. By including similarly high spatial resolution near-infrared photometry and using a Bayesian fitting routine developed at the University of Florida, the team was able to accurately reproduce the high spatial resolution measurements with a clumpy torus model. This is consistent with the objects having a torus scale of < 5 parsecs. Interestingly, for the Seyfert 2 objects, it was found that the number of clouds along an equatorial view is as low as 5-15, although the total population of clouds number in the thousands.

Most recently, near-infrared IFU observations using the Near-infrared Integral Field Spectrometer (NIFS) with adaptive optics have probed one of the closest AGN, NGC 4151 (at 13.3 megaparsecs), in unprecedented, diffraction-limited detail (see Figure 2, previous page). This work, led by T. Storchi-Bergmann (Insitiuto de Fisica, Universidade Federal



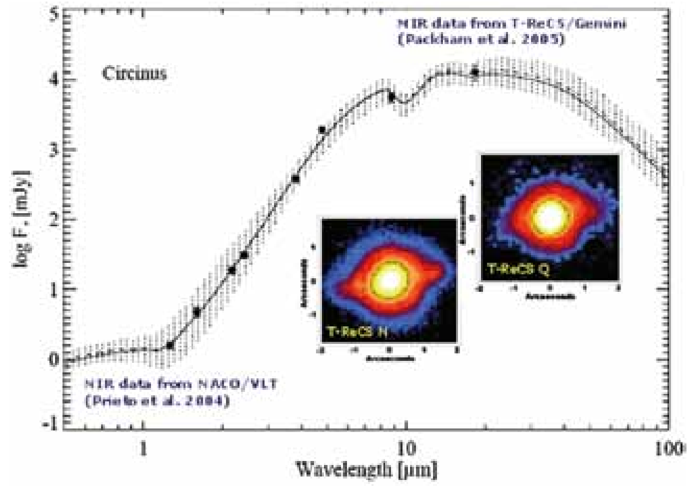


Figure 4 (above): M87 jet is shown at various wavelengths, including the Gemini near-infrared OSCIR data at lower right.

Figure 5 (right): high spatial resolution infrared SED of the Circinus galaxy fitted with the clumpy torus models. Solid and dashed lines are the best fitting model and that computed with the median of each of the six parameters that describe the models. The shaded region indicates the range of models compatible with a 68% confidence interval around the median. T-ReCS N and Q images (8.8 and 18.3 microns, respectively) are also shown.

do Rio Grande do Sul – UFRGS, Brazil), mapped the excitation and kinematics of the gas and studied the feeding and feedback occurring near the core of this AGN. The team finds that most of the ionized gas originates in a biconical outflow—thus mapping the AGN feedback—whereas most of the molecular gas originates in the galaxy plane, in orbit around the supermassive black hole and is probably the source of the AGN feeding. The team further estimates the mass of the ionized gas at 2.4 million solar masses and molecular gas at only 240 solar masses. Nevertheless, they argue that near-infrared molecular gas emission maps only the "hot skin" of a probably much larger colder molecular gas reservoir. They also find a nuclear red source, whose spectrum is consistent with that predicted for a dusty torus with temperature T ~ 1300 K surrounding the AGN. As in previous studies, this source is unresolved, but the observations do provide an upper limit for its distance from the nucleus of four parsecs. Bergmann et al. have published over 10 additional papers based on Gemini IFU observations of NGC 4151 and three other galaxies (ESO 428-G14, NGC 4051, and Mrk1066) and found similar results to those of NGC 4151.

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Supernovae

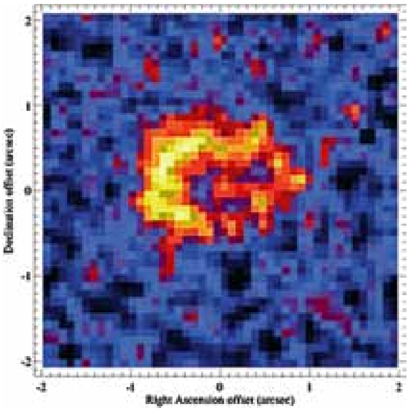
Supernovae, like Gamma-ray Bursts, their even higher-energy cousins, are a nearly perfect match for Gemini's capabilities and queue-based operational approach. Access to a broad swath of the infrared/optical spectrum, and the ability to provide rapid-response follow-up observations, make Gemini an excellent supernova science machine. Rapid response was critical for observations of SN 2008D in NGC 2770, which produced bright X-ray/ultraviolet emissions detected by NASA's *Swift* satellite in early March 2008. Within 1.7 days, Gemini initiated a sequence of events to obtain optical spectra chronicling the birth of a supernova in real time (Modjaz et al.). However, it was one of the initial commissioning datasets from the Gemini Multi-Object Spectrograph (GMOS) at Gemini North in late 2001 that delivered one of Gemini's first major results in the study of exploding stars.

The supernova, designated SN 2003gd, came to the attention of Australian amateur astronomer and supernova hunter Rev. Robert Evans when he noticed a new star as he visually scanned the nearby galaxy M74 (NGC 628) through his 31-centimeter (12-inch) telescope in June 2003. Shortly after this discovery, a team led by Stephen Smartt and Justyn Maund (University of Cambridge, UK) found that the Gemini GMOS commissioning images of the galaxy (see Figure 1), clearly recorded the progenitor star. The science-grade data they found in the Gemini Science Archive (GSA) included g-, r-, and i-band images taken under excellent seeing conditions. From the Gemini (and additional *Hubble Space Telescope*) data, the team identified and characterized the progenitor star's temperature, luminosity, radius, and mass. From this, the team concluded that the star was a normal, massive, red supergiant, much like the closer and well-known star Betelgeuse, which will likely meet a similar fate relatively soon. Additional observations by Smartt's team confirmed that SN 2003gd was a normal Type II supernova, making this the first time that a red supergiant progenitor star had been identified "on its deathbed" prior to going supernova. In September 2008, Maund and Smartt also led another *HST*/Gemini program to look for the progenitor. However, it was gone, providing verification of its pre-explosion identity.

SN 2003gd was also scrutinized by a large international team of scientists, this time to look for evidence of dust. In August 2004, team-members Doug Welch (McMaster University) and Geoff Clayton (Louisiana State University) used GMOS again to take deep optical spectra of SN 2003gd and look for the effect of extinction by dust via its impact on the Hα emission peak. The team's detection made it clear that large quantities of dust (on the order of 0.02 solar mass) could be produced in a very short period of time after a supernova explosion of this type.

About two years earlier, another team led by Patrice Bouchet (CTIO), this time using the mid-infrared instrument T-ReCS on Gemini South, announced the detection of lesser amounts of dust around the more evolved (as well as closer and more famous) supernova remnant SN 1987A (see Figure 2, page 34). The closest observed supernova of the past 400 years, SN 1987A allowed the team to resolve a well-defined dust ring with the T-ReCS data. Augmenting the Gemini

Figure1: Gemini GMOS image of M-74 (NGC 628) with inset (left) showing pre-explosion star (enhanced) from Gemini image. Right inset image shows the supernova six months after it exploded (right inset image from Isaac Newton Telescope).



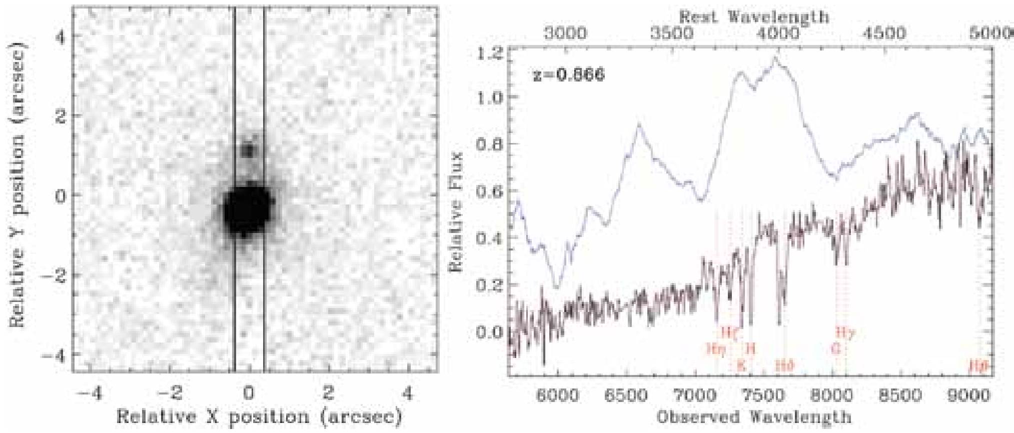


Figure 2: (above left), This T-ReCS mid-infrared image reveals a dusty equatorial ring around Supernova 1987A as well as a faint trace of the explosion ejecta.

Figure3: (above right), Example GMOS data for one of the SNLS supernovae at z = 0.87 (i' = 24th magnitude). Left: 9 × 9 arcseconds section of the GMOS acquisition image showing the host galaxy (below) and the supernova above. The approximate position of the spectroscopic slit is shown: spectra of the supernova and its host are obtained simultaneously. Right: extracted GMOS spectrum of the host galaxy (lower, in black) showing narrow absorption features that are used to measure the redshift. Above (in blue) is the smoothed spectrum of the supernova showing the characteristic broad features of Type Ia SNe.

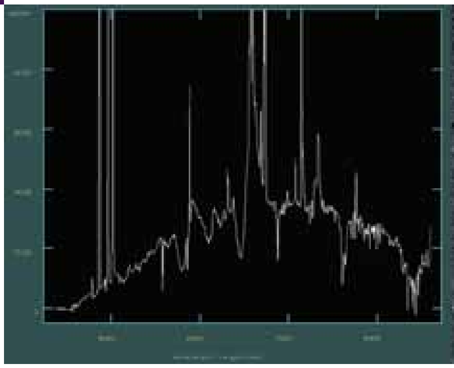
data with X-ray observations from the *Chandra Space Telescope* and radio data from the Australian National Telescope Facility, the researchers found strong confirmation that dust is a key product of supernova explosions.

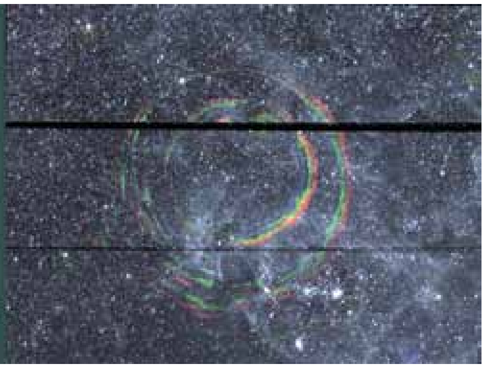
Another type of supernova, Type Ia (SNe Ia, thought to be the result of a white dwarf amassing material from a companion until the white dwarf becomes unstable and explodes) is the subject of a multi-observatory program, including Gemini, called the Supernova Legacy Survey (SNLS). Concurrent with the SNLS, Gemini also participated in a smaller, similar survey called ESSENCE (Equation of State: SupErNovae trace Cosmic Expansion). The primary goal of the SNLS (and to a large extent ESSENCE) is to better understand the nature of "dark energy" and, by assembling a large sample size (over 500 SNe Ia), to determine dark energy's average equation of state parameter (w) and ultimately determine (to 3σ) if dark energy is something other than a manifestation of Einstein's "cosmological constant." Dark energy is the force that is accelerating the expansion of the universe and is thought to encompass about 70 percent of the energy budget of the universe.

The SNLS targeted SNe Ia in the redshift range of z = 0.3-0.9 from wide-field Canada-France-Hawai'i Telescope (CFHT) images, which revealed an average of 40 candidates per month. In addition to Gemini and CFHT, the W.M. Keck Observatory and the Very Large Telescope (VLT) were the key partners in the SNLS effort. During the five-year life of the survey, from 2003-2008, the Gemini Multi-Object Spectrograph (GMOS) observed almost 300 targets, of which almost 200 were SNe Ia supernovae. Many of the fainter, more challenging observations were assigned to Gemini due to the extreme sensitivity and high signal-to-noise ratio made possible by the use of the Nod & Shuffle technique on GMOS to obtain optical spectra (see sample in Figure 3 and a full description of the Nod & Shuffle technique on page 58).

The SNLS survey continues to have a long and prosperous legacy. As of early 2010, about 20 refereed papers based on its data have entered the astronomical literature. These papers cover topics such as dark energy, rates of supernovae, and a 2010 paper (Sullivan et al., in press) which found that the intrinsic brightness of Type Ia supernovae are even more dependent upon galaxy type than previously suspected; this will have profound implications for future SNe Ia cosmological analysis.

While Gemini excels at supernova research by adjusting quickly to transient events, at the other extreme is the study of supernova light echoes. By their very nature, supernova light echoes can be seen hundreds or even thousands of years after the explosion, but they offer astronomers a chance to literally look back in time and, like a detective, unravel the nature of a supernova whose light has long faded. The principle is easy: as the light from a supernova travels through space, it encounters gas clouds that reflect the light in all directions, including toward us. By expanding the light from the echo into





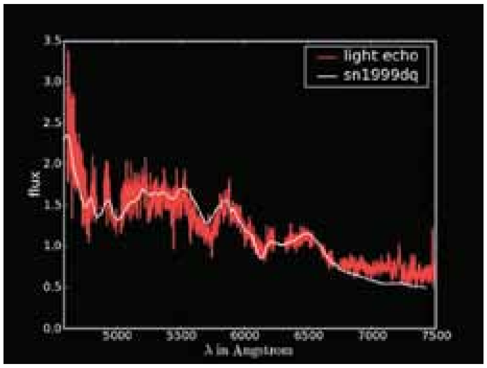


Figure 4 (above left): GMOS-S spectrum of the brightest portion of a SN1987A light echo obtained on December 24, 2006. (Sharp vertical lines are imperfectly subtracted Large Magellanic Cloud field emission lines and night sky lines.) The Type II outburst spectrum of SN1987A is clearly seen in light reflected from dust in the vicinity of the supernova, which occurred 20 years earlier. (center) A composite image of the region around SN1987A (created by Pete Challis (SuperMACHO project). Difference images at intervals of three years are superimposed on this region. Blue indicates the earliest difference image and red the most recent.

Figure 5 (above right): GMOS-South spectrum of the light echo from SNR 0509-67.5. Overplotted in white is the spectrum of SN 1999dq, one of the sample of nearby supernova which best matches the observed light echo spectrum.

a spectrum, astronomers can identify characteristic spectral features and identify what type of supernova occurred. Results from the more recent SN 1987A provide a "control" as seen in Figure 4. A more dramatic result came by using the Nod & Shuffle technique with GMOS on Gemini South, which produced a spectrum from light echoes still resonating over 400 years after a star exploded and creating what is now known as SNR 0509-67.5 in the Large Magellanic Cloud. The spectrum (Figure 5) revealed beyond any reasonable doubt that this was a Type Ia event.

The study of supernovae has proven extremely well-matched to Gemini's capabilities. Demand for Target of Opportunity observations of newly exploded stars continues to run high, as these data help answer questions about how and why they explode. The study of supernovae might someday even lead to an understanding of the mysterious dark energy and even the ultimate fate of our universe.

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Star Birth in the Early Universe

Studying the ebb and flow of galactic star formation, especially in the early universe, plays to Gemini's strengths in integral-field and deep-infrared spectroscopy. This topic is also chock-full of surprises. Important Gemini results reveal extremely efficient stellar "birth control" at an epoch when the universe was only a quarter to a third of its current age ($2 < z < 3$, a look-back time of about 11-12 billion years). This is a period when massive galaxies might seem ripe for stellar proliferation, but almost half of them have strongly suppressed star-formation. Looking so far back in time, these results provide additional evidence for the frenzied growth and formation of massive galaxies very early in the universe which was then somehow quickly truncated (see story on Gemini's legacy of research on galactic evolution starting on page 40 of this issue).

Two of the key programs shedding light on how active star formation in galaxies may be squelched to produce massive, apparently mature galaxies seen at $z = 2$ use very different approaches: one is a survey of distant galaxies to identify suitable candidates in detail, with a detailed follow-up on a single target; the other dissects a quasar's light to help unravel the processes occurring deep inside.

The survey, led by Mariska Kriek (Princeton University) et al. (2006), identified 20 (as of 2006, currently there are 26 in the sample) relatively massive galaxies (from the Multiwavelength Survey by Yale-Chile (MUSYC)) with redshifts between $2.0 < z < 2.7$. This redshift range was selected so that the Hα emission line (a key tracer of active star formation) would fall within the K-band atmospheric window. It was found that nine of the galaxies in this (2006) sample (45 percent) displayed no emission lines in their rest-frame spectra (Figure 1). The Gemini Near-Infrared Spectrometer (GNIRS, then at Gemini South) provided the spectra which the team used to measure the equivalent width of the Balmer Hα line and derive the ratio of current to past star formation. The results from the sample ranged by a factor of 100 in star formation rates between the least (non-zero) and most active galaxies of the survey. Both the Hα measurements and the stellar continuum modeling imply that star formation in these galaxies has been strongly suppressed into quiescence.

To follow up on this work, Kriek et al. (2009) obtained what is still thought to be the deepest single-slit, near-infrared spectrum ever taken of a galaxy with a redshift greater than 2. The target, 1255-0—one of the nine galaxies from the earlier 2006 survey that showed only very weak Hα emission—was integrated for about 29 hours using the Gemini Near-Infrared Spectrograph (GNIRS) on Gemini South (see Figure 2) to reveal the detection of emission line ratios (for [NII/Hα], [SII/Hα] and [OII/OIII]). These ratios allow estimations of star-formation rates and ionization within the interstellar medium, which in turn shows that we are witnessing less than 1 percent of the galaxy's past average star formation. To account for the number of stars, these results indicate that this galaxy had a "wild past," especially compared with the relative abstinence seen at these galaxy's current epoch. In addition, absorption lines in the spectrum allowed, for the first time, an accurate redshift determination for this galaxy type by stellar absorption lines.

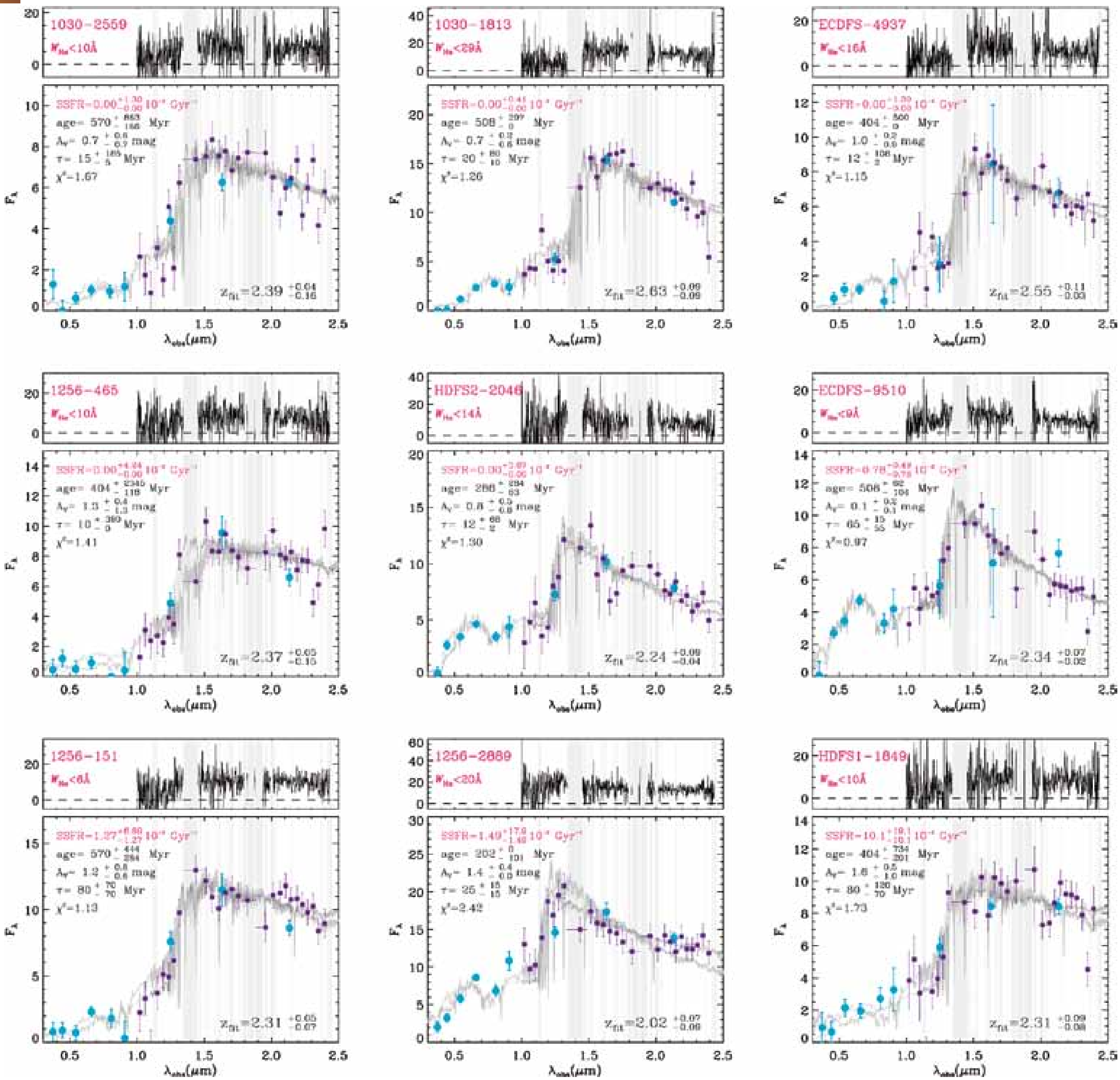
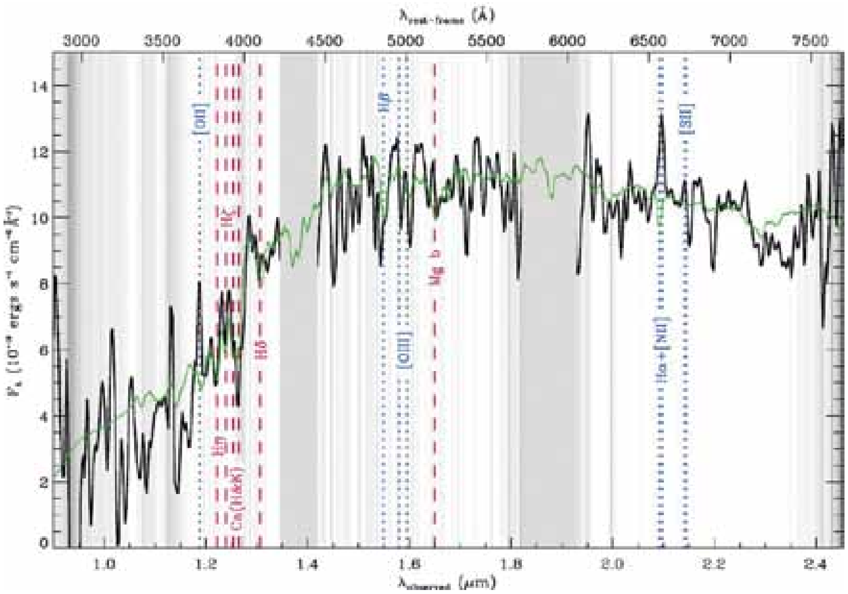


Figure 1: GNIRS infrared spectra (purple) and optical to near-infrared photometry (blue) of the nine "dead" galaxies. These galaxies show no (Hα) emission, which indicates that their star formation rates are extremely low. The upper panels show the original GNIRS spectra.

A general dearth of spectroscopic data on galaxies of this type and redshift (age) make it very difficult to piece together an evolutionary scenario—one that explains how these galaxies can so quickly go from what must have been a remarkably frenzied period of star birth in the early universe to the quiescent phase that we see, even at redshifts of around 2.

Hence, to understand what processes might squelch star formation in massive galaxies in the early universe, David Alexander (Durham University UK) led a team that used Gemini's Near-infrared Integral Field Spectrometer (NIFS) on Gemini North (see full-length article on this work in this issue of *Gemini*Focus starting on page 70). Alexander's target was an actively star forming galaxy: SMM J1237+6203 at z = 2.07. Unlike much rarer quasars (which are known to have galaxy-wide outflows), this galaxy is radio quiet, suggesting it may be the star formation (rather than the super-massive



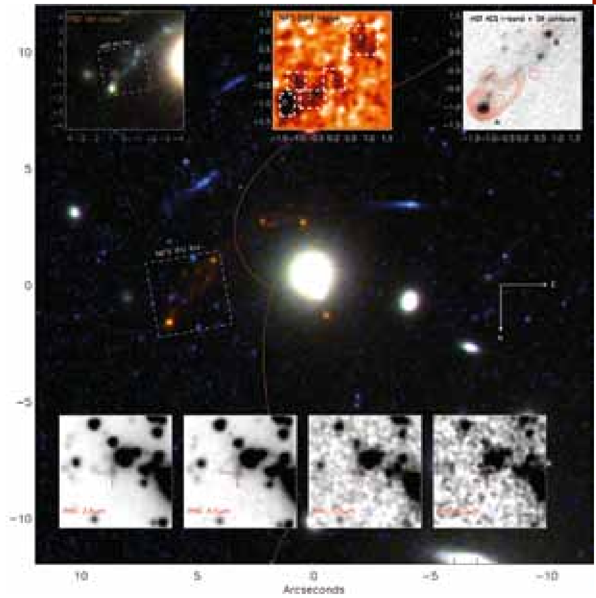


Figure 2: (above left), (a) Spectrum of 1255- 0, obtained over the course of 6 nights with GNIRS on Gemini South.

Figure 3: (above right), Color composite HST ACS VRI-band image of the lensed z = 4.92 galaxy behind MS 1358+62 with the z = 4.92 critical curve from our best-fit lens model overlaid. The HST images clearly show the multiply imaged galaxy as two mirror images which are folded about the critical curve (red line resolved into two images of the back-ground galaxy). The morphology of the galaxy is clearly dominated by up to six star- forming regions surrounded by a dif-fuse halo. The upper middle panel shows the white light (wavelength collapsed) im-age of the [OII] emission from the IFU; the boxes labeled 0-4 denote the regions from which spectra were extracted .

black hole at the galaxy's center) which is producing the mechanical energy required to eject gas from the galaxy. The observations reveal a galaxy-wide outflow with sufficient energy to easily pump material out of the galaxy, removing the material from which future generations of stars would have formed and hence, effectively truncating star birth process. Possible explanations for what powers the outflow range from central black hole fueled active galactic nuclei (AGN) to supernovae winds, or (most likely) a balanced combination of both. These observations begin to provide tentative evidence for an evolutionary link between strong star-forming galaxies which can quickly expel their gas in this strong feedback mode to eventually form "red and dead" galaxies, as studied by Kriek et al.

Looking back further in time to study the state of affairs of the first primitive galaxies within the first billion years of the Big-Bang, Mark Swinbank (University of Durham, UK) et al. took advantage of one of nature's largest lenses to probe the properties of a highly magnified, star-forming galaxy at z = 4.92 behind the galaxy cluster MS 1358+62. Using the Gemini near-infrared integral field capability on GNIRS (together with imaging from *HST* and *Spitzer*), Swinbank and his team mapped kinematics and star-formation properties using the nebular [OII] 3727 emission line doublet. These data spatially resolve the distribution of star formation and dynamics (see Figure 3 & 4), and also provide evidence for a galactic-scale outflow (estimated to be young, less than 10 million years). The team was also able to isolate and estimate the sizes, masses, and star-formation rates for two of the brightest HII regions in the galaxy on scales of just 100 parsecs and they found them to be comparable in mass and density to those found in local massive star-forming HII regions. However, these HII regions in the young universe have star-formation rates more than100 times the rate typical of HII regions in the local universe.

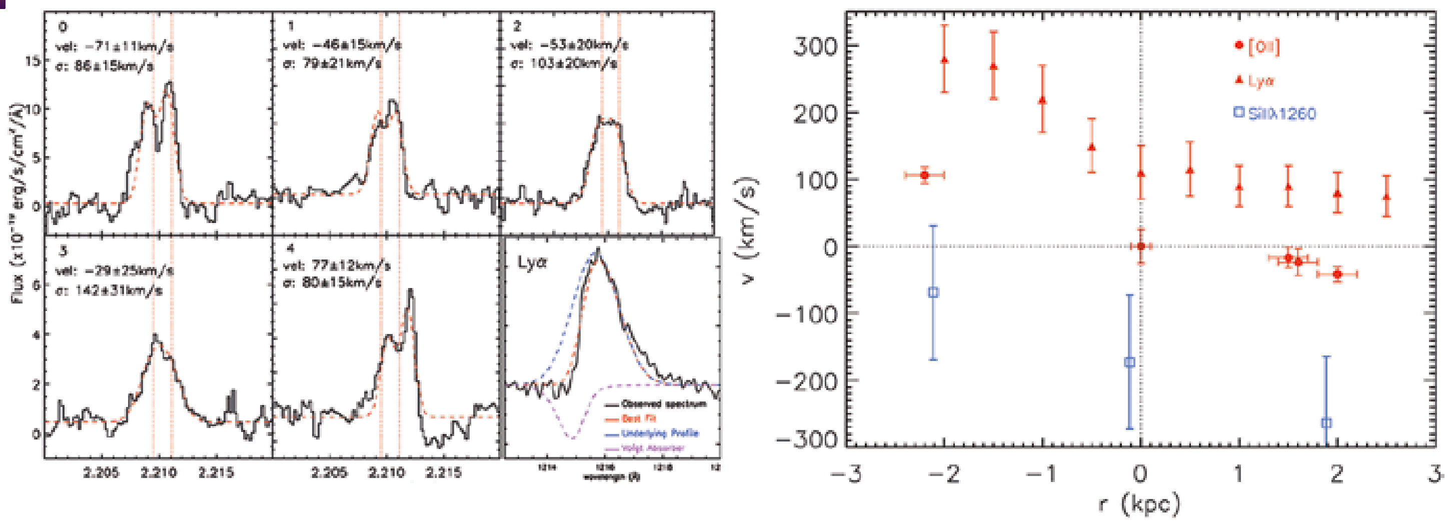


Figure 4: (left), A one- dimensional spectrum of the five star-forming regions within the z = 4.92 galaxy from the NIFS IFU observations. In all panels the position of the [OII] 3726.8, 3728.9 doublet is at a fixed redshift of z = 4.9296. The final panel shows the one-dimensional spectrum of the z = 4.92 galaxy around the Lyman- alpha emission. (right) The extracted, one- dimensional velocity gradient along the long axis of the galaxy (source plane).

Future research on galactic star birth will undoubtedly continue to excel at Gemini. Integral field unit studies of other galaxies will establish trends by increasing sample size and diversity of galactic masses and redshift. Further probing in the mid-infrared will penetrate possible obscuration of star birth that might have been hidden in previous near-infrared studies such as those described in this article. Laser guide star adaptive optics will continue to improve spatial resolution, and infrared sensitivity will improve. This will allow Gemini to more efficiently collect and analyze radiation from energetic outflows, leading to a more complete understanding and characterization of star birth as galaxies evolve.

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Bringing Early Galactic Evolution into Focus

Galaxies are fundamental building blocks of the universe. Understanding them and how they evolve is at the core of any complete and coherent cosmological picture. Galactic evolution established an important place in Gemini's "discovery space" very early in the observatory's history and has remained there ever since.

All things being equal, a larger telescope aperture enables the study of galactic evolution by collecting more photons from distant galaxies at higher redshifts—therefore enabling ultra-deep spectroscopy at greater look-back times. The use of a telescope as a time machine is nowhere more important than in the understanding of how galaxies form and evolve from the early universe into what we see around us today.

Exemplifying this emphasis on the study of early galactic development, the Gemini Deep Deep Survey (GDDS) began observations in 2002 conducted by a large international team led by Roberto Abraham of the University of Toronto, Karl Glazebrook (Johns Hopkins University now at Swinburne University, Australia), and Patrick McCarthy (Observatories of the Carnegie Institution of Washington). The team used the Gemini Multi-Object Spectrograph (GMOS) not very long after this powerful optical spectrograph/imager first began collecting light at Gemini North. The GDDS program required over 120 total hours of telescope time in the GMOS multi-object spectroscopy mode, allowing the team to obtain nearly 100 spectra simultaneously in single pointings (see Figure 2, page 42). "This is a lot of valuable time on the sky, but when you consider that it has allowed us to help fill in a crucial 20-percent gap in our understanding of the universe, it was time well spent," adds Glazebrook (who did this work while at Johns Hopkins University).

Figure 1: (facing page), Postage-stamp sized images (from GDDS Paper VIII) showing the morphologies of the 54 galaxies in the GDDS sample with $\log_{(\text{STELLAR MASS})} > 10.5$. These galaxies are sorted in order of decreasing redshift. Early-type galaxies are circled. Each image is 5 × 5 arcseconds in size, with galaxy ID number, spectroscopic classification, redshift confidence class, rest-frame (U-B) color, redshift, and stellar mass. Objects without high-confidence spectroscopic redshifts have their redshifts labeled in parentheses. The border of each galaxy image indicates the spectroscopic classification. Red borders indicate evolved spectra. The gray regions surrounding groups indicate which of three broad redshift bins the objects fall within.

However, to execute this program it was necessary to go beyond raw aperture and develop a technological and observational advantage that would allow galaxy spectra to be obtained in the so-called "redshift desert." This desert isn't necessarily one of absence, it's simply a consequence of not being able to easily detect key spectral signatures of galaxies between redshift $z = 1.4 - 2.5$ due to interference by natural atmospheric telluric luminescence (skyglow). To overcome this problem, a technique, still only available on Gemini for an 8- to 10-meter-class telescope, was integrated into the Gemini telescopes. Called Nod & Shuffle (N & S), this method uses a CCD control technique called 'charge shuffling' to record near-simultaneous images of galaxies and nearby sky and allow accurate subtraction of atmospheric emission. This reduces noise that would otherwise prevent the detection of faint spectral features in distant astronomical objects. (see a description of the N & S technique on page 58). Glazebrook helped develop the use of N & S with Joss Hawthorn (Anglo-Australian Observatory, AAO) for faint galaxy observations while at the AAO.

By providing a powerful platform for the GDDS to succeed, GMOS spectroscopic observations of over 300 galaxies (see examples in Figures 1 & 3) revealed that galaxies at this epoch (when the universe was only 3-6 billion years

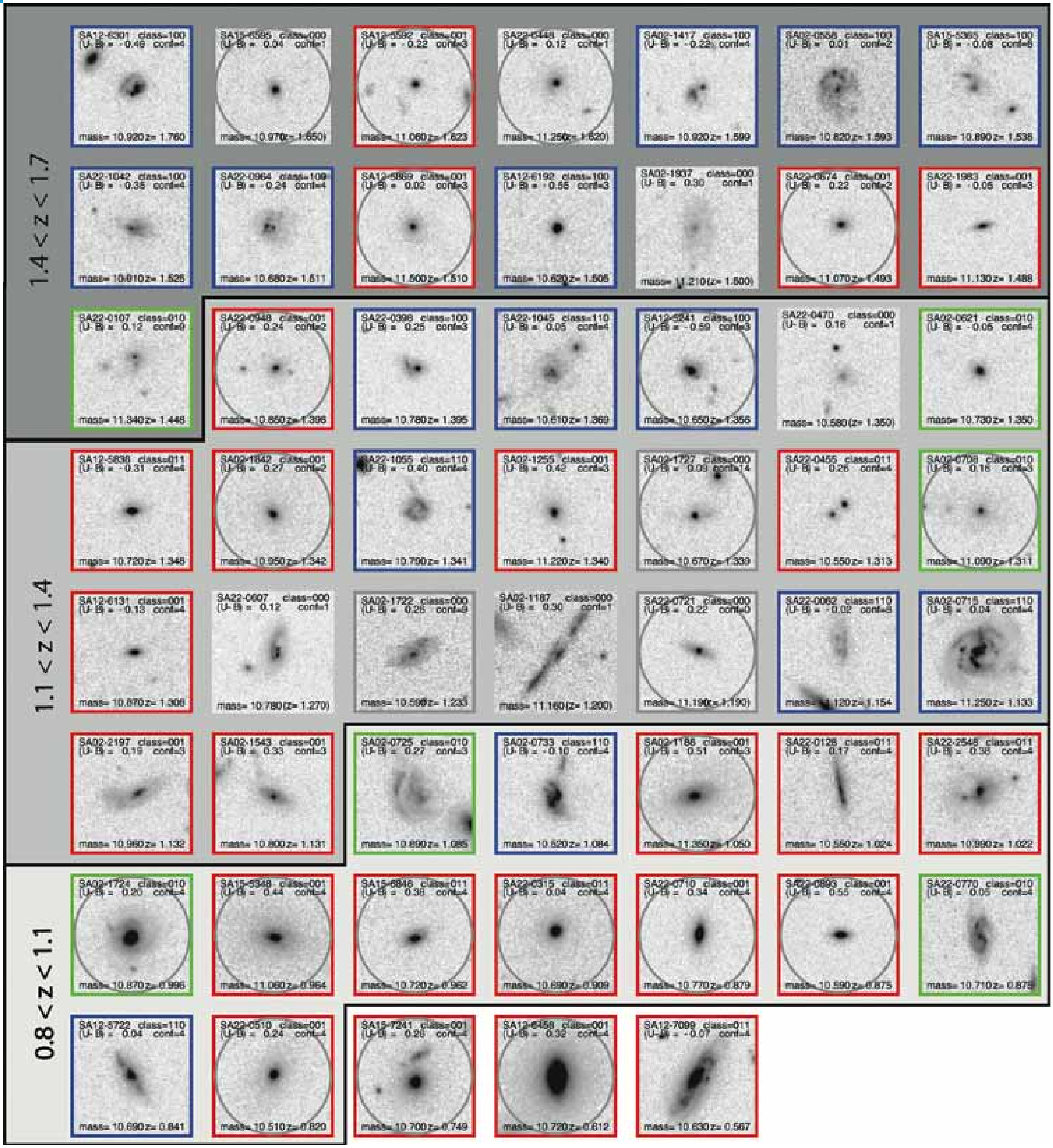
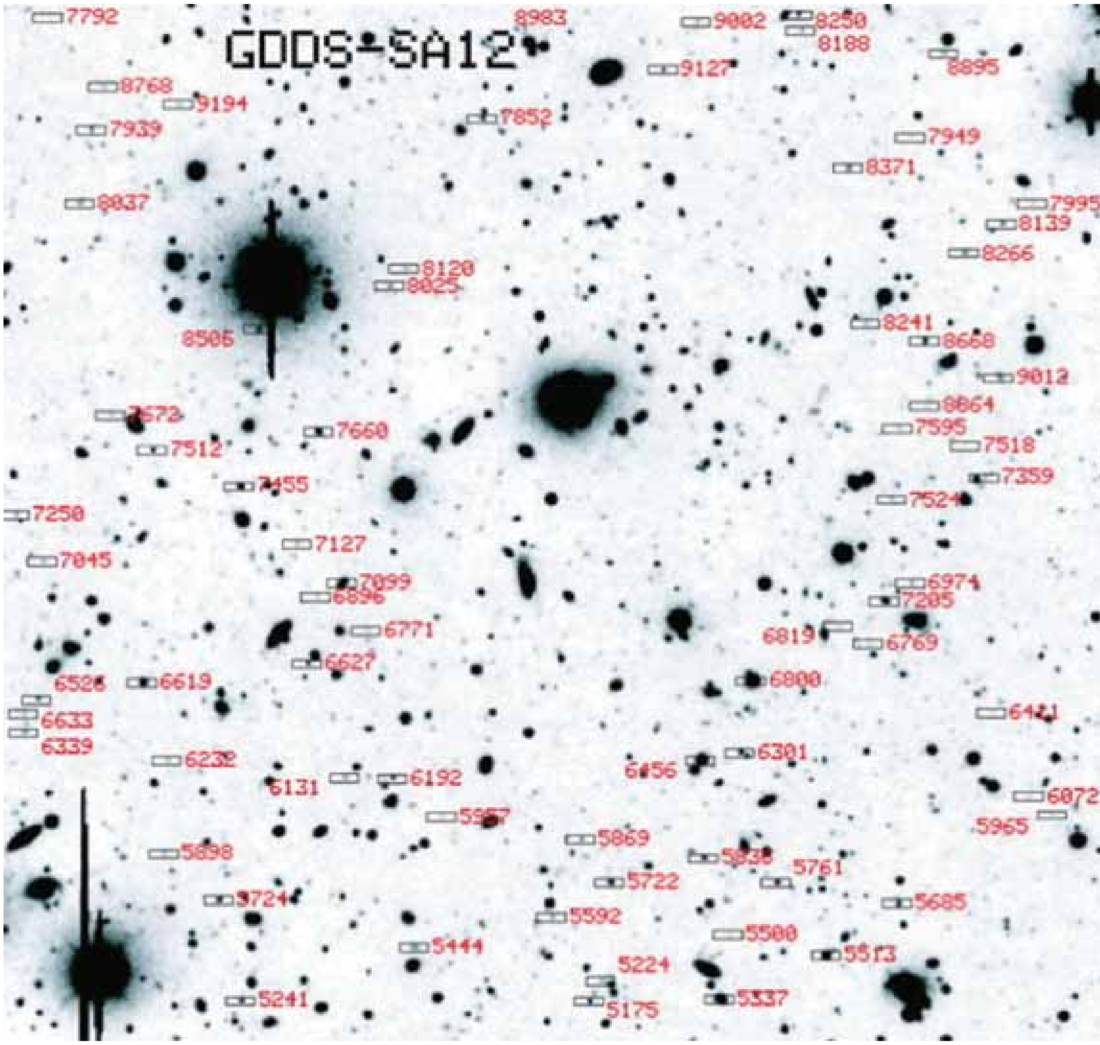

1.4 < z < 1.7
1.1 < z < 1.4
0.8 < z < 1.1

Figure 2: (right), The GDDS-SA 12 field is shown as an example of the multi-object spectroscopy used for the GDDS. The field size is 5.5 x 5.5 arcminutes[2] and the small rectangles correspond to the positions of the distant galaxies selected for GMOS spectroscopy. The background image is a 180-minute I-band exposure taken with the CTIO 4-meter telescope.



old) do not behave as many theorists expected. The early papers from this work (there are currently 11 in a series of papers based mostly on GDDS, or related, observations) revealed that many more than expected massive galaxies were essentially fully formed by the epoch surveyed in the GDDS. Popular hierarchical models predicting that these galaxies would still be accreting from smaller building blocks were dealt a severe blow. “It’s as if a teacher walked into a classroom expecting to greet a room full of unruly teenagers and found well-groomed young adults instead,” said Abraham in a major press conference at the 203rd meeting of the American Astronomical Society in Atlanta, Georgia, in January 2004.

Additionally, in a sub-sample of 13 GDDS galaxies with high star-formation activity, it was found that massive galaxies had stronger than expected interstellar medium absorption (due to singly ionized iron, magnesium, manganese, and neutral magnesium, see Figure 4) compared to low mass galaxies seen in absorption against background quasars. The implication is that past generations of short-lived massive stars had already flooded the interstellar medium and increased interstellar metallicity within these galaxies in the very early stages after the Big Bang.

A profound ramification of the GDDS work (which has since been reinforced by other studies, ie. di Serego Alighieri et al. and Jørgensen et al.) is that there is precious little time for the formation of the most massive galactic specimens seen in these GDDS data and the well-established beginning of the universe about 13.7 billion years ago. It has been suggested that massive black holes were much more ubiquitous than previously thought in the young universe and acted as efficient seeds for the rapid formation of the first galaxies. Resolving this inconsistency is why the GDDS papers are among the most highly cited of any Gemini research and already part of the legacy that Gemini is leaving to future generations in the study of our universe.

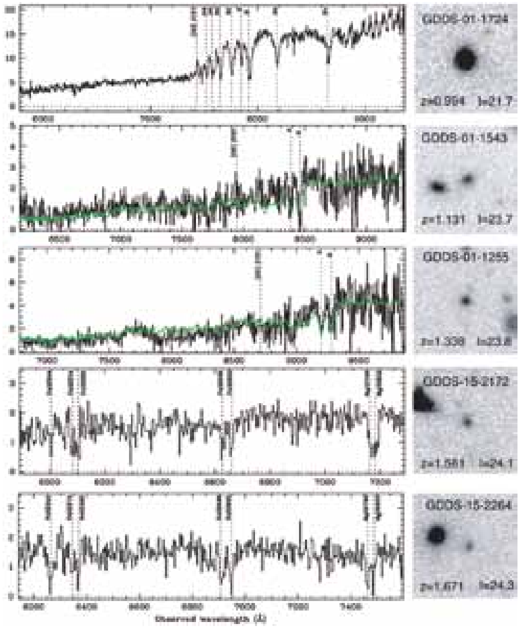


Figure 3: (left), Montage of 100 kilosecond Gemini GMOS nod-and-shuffled spectra from the GDDS. Ground-based I-band images (in ~0.8 arcsecond seeing) are shown at right. Objects shown span a redshift range of 0.994<z<1.671 and a magnitude range of 21.7<I<24.3. A post-starburst system with prominent Balmer-absorption features is shown at top followed by two quiescent early-type systems (with early-type spectral templates superimposed). About 40 percent of the red population shows similar spectra. The bottom two spectra show blue ultraviolet continua, consistent with recent star formation, together with narrow interstellar medium (ISM) absorption lines (MgII, FeII).

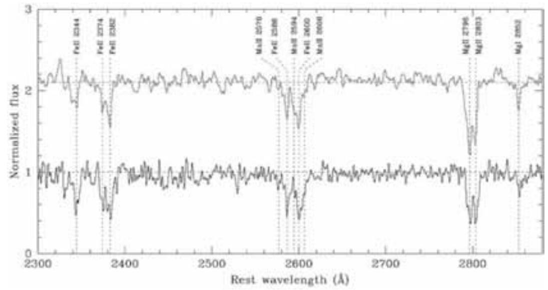


Figure 4: (above right), Lower black curve: Composite GDDS spectrum of 13 galaxies with strong ISM absorption lines. The redshift range covered by the spectra is 1.260<z<1.895 (with a mean of z=1.53). This sample represents about 29 percent of the total number of galaxies detected by the first two masks of the GDDS in the redshift interval 1.13<z<2.00. Detected absorption features are marked by the dotted lines. As a reference, the composite spectrum of 14 local starburst-dwarf galaxies observed with HST/FOS is shown as the upper gray curve. This spectrum has been magnified for comparison.

The GDDS data have already been used for an additional five papers that combine these Gemini data with other datasets (e.g. the *Hubble Space Telescope* and the *Spitzer Space Telescope*) to broaden the legacy of the Gemini observations.

After helping to establish a foundation in our understanding of the early evolution of galaxies, this topic will undoubtedly continue to flourish at Gemini. As new technologies such as Multi-Conjugate Adaptive Optics (see MCAO and the Study of Galaxies at z>1 by Inger Jørgensen, *Gemini*Focus, December 2007, pg. 27-31) complement optical and infrared multi-object and integral-field spectroscopy, Gemini will probe morphologies and expand sample sizes. A clearer picture of the early universe will emerge from the solid foundation that programs like the GDDS have already provided.

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Gamma-ray Bursts

If an event in the universe could be perfectly matched for an observatory, it would be hard to imagine a better coupling than Gamma-ray Bursts (GRB) with Gemini. GRB evolve very rapidly and are the most energetic explosive events known in the universe since the Big Bang. They radiate prodigious amounts of energy but generally happen at tremendous distances away, making them appear faint (see GRB background information on page 47). Timing is everything when it comes to studying GRB, and Gemini's multi-instrument queue provides the temporal, spectral, and technological flexibility to literally catch these transient, fleeting events "in the act."

Since their discovery in 1967, GRB have been elusive and difficult to study due to their faint optical/infrared brightnesses and short lifetimes. Initially, astronomers struggled to determine if these events happened in the local universe or were cosmological in nature. Over the past decade, Gemini has been instrumental in raising the distance bar for GRB and now their distances and simple optical/infrared spectroscopic signatures make them critical probes into the high-redshift, distant universe. The temporary afterglow of a GRB is a beacon of light that allows us to sample difficult-to-study, far-off realms, such as the interstellar medium in star-forming galaxies, the intergalactic medium (IGM), and especially star-birth rates in the very young, immediate-post re-ionization universe. The fleeting optical/infrared afterglow is also critical because it allows astronomers to determine the distance to a GRB, see Figures 1 and 3)

Gemini's impact on the field of GRB began when the argument over what constraints might limit the two varieties of GRB (short-hard and long-soft) was just being formulated. At that time (pre-2005), the optical afterglow from short-hard GRB was still unobserved; meanwhile, the long-soft variety was being detected optically and expanding the range of redshifts on both ends of the distance scale. This eventually presented the possibility that long-soft GRB could be part of a continuum of stellar-mass explosions connected to supernovae seen in our local universe. Gemini played a critical role in the study of the most significant connecting link between GRB and supernovae (SNe)—an event called XRF 060218 (see Figure 2). Three days after the *Swift* satellite detected a burst on February 18, 2006, Gemini data revealed that a supernova was associated with this burst. This linked the event to the death of a massive star at a redshift of only about 0.033 (making it one of the nearest GRB ever detected, at a distance of only about 466 million light-years). The spectrum indicated that the supernova had properties placing it somewhere between those of previous GRB-SNe and ordinary Type Ibc supernovae observed in the local universe.

At the other end of the distance scale, speculation about the high-end redshift limits for GRB began a race to discover how deep these events could penetrate into the early universe. By the mid-2000s, Gemini was routinely obtaining absorption spectra for GRB between $1< z <5$, and speculation that the limits could go higher was common. Part of the problem is that at about $z>7$, a physical "wall" exists to optical detection because of complete absorption of the Lyman-alpha suppressed GRB spectrum due to neutral hydrogen in the IGM. This requires observing in the infrared—a winning hand for Gemini.

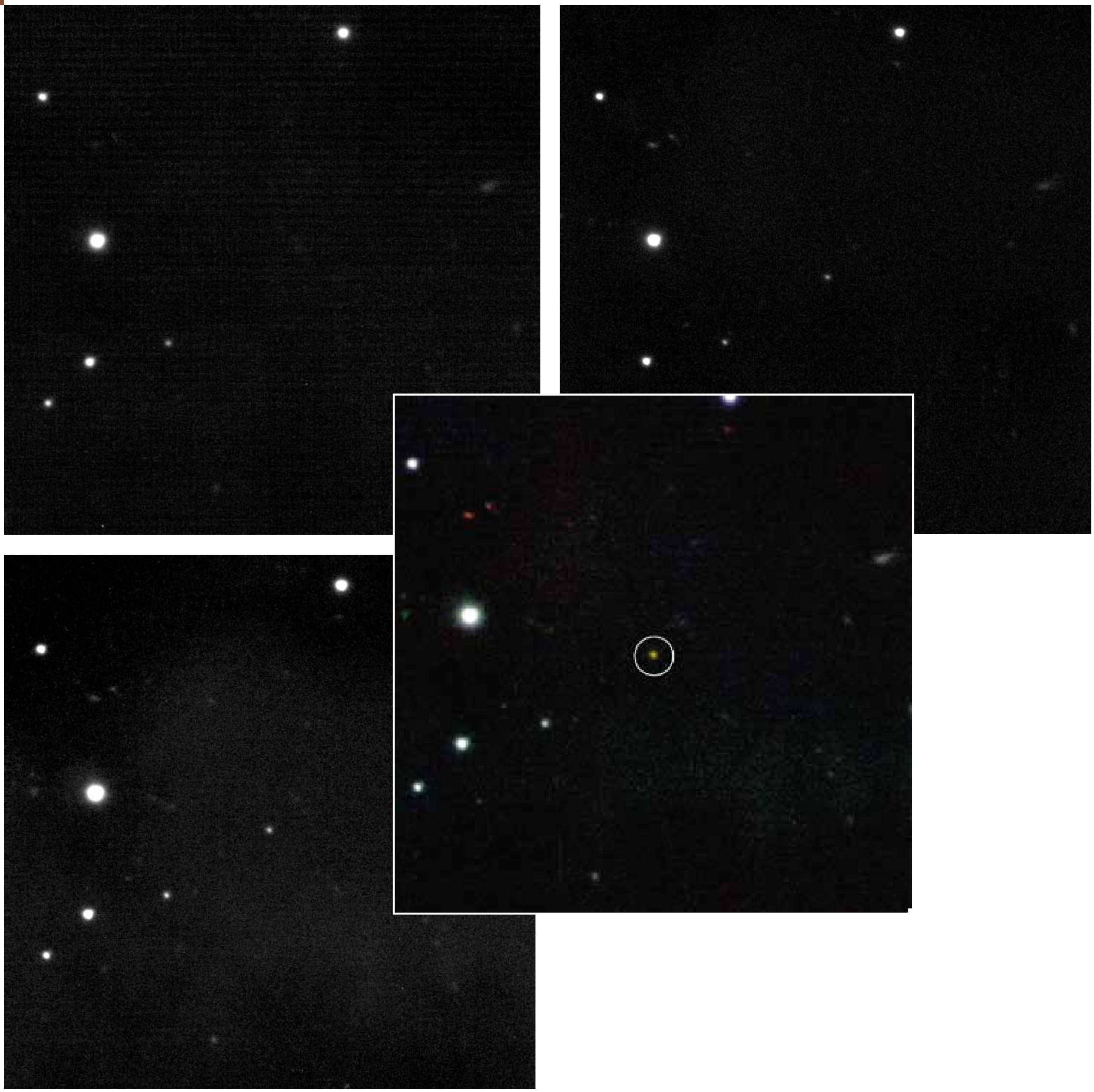
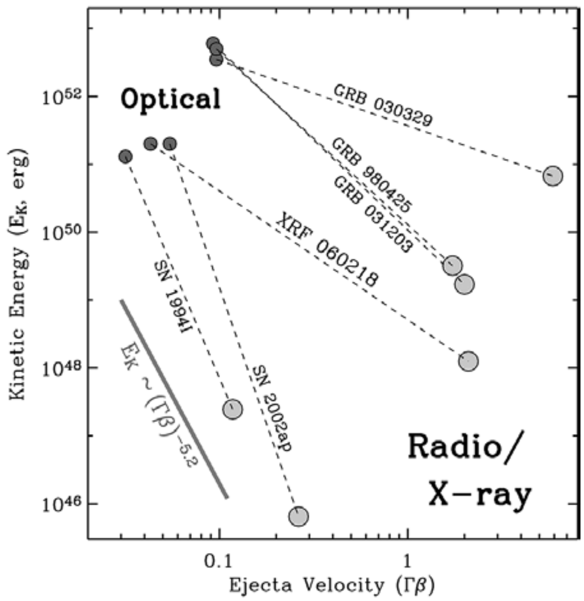


Figure 1 (above) The fading infrared afterglow of GRB 090423 is shown at center in a false color image from Gemini North NIRI Y-, J-, and H-band images (left-right, top-bottom respectively) shown in background. These images were used with a K-band image from the United Kingdom Infrared Telescope to approximate the GRB's redshift which is currently the most distant object ever seen in the universe.

In an article by Edo Berger (Harvard), and Alicia Soderberg (Harvard), published in the June 2007 issue of *Gemini*Focus, it is stated that, "…our current gamma-ray program at Gemini is indeed focused on rapid near-infrared imaging of burst afterglows in order to increase the number of high redshift gamma-ray bursts and hopefully in the near future detect the first objects at $z > 7$." In less than two years, Gemini would be instrumental in making this prediction prophetic, and in the process, taking humanity's vision to new limits.

On April 23, 2009, a long-duration GRB triggered an alert from the *Swift* satellite, prompting Gemini (through a Target of Opportunity program) and other large telescopes to scramble and collect photons from a burst, dubbed GRB 090423, that would prove to be at the very edge of the observed universe. The first telescope on the scene was Gemini North's neighbor the United Kingdom InfraRed Telescope (UKIRT), which obtained the initial infrared image (K-band, at 2.15



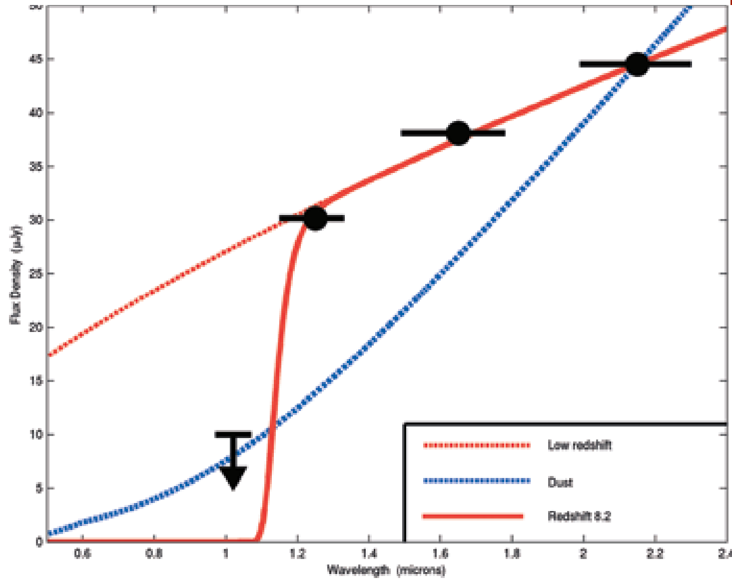


Figure 2 (above left): The outflow kinetic energy, EK, of cosmic explosions may be probed through optical, radio and X-ray observations and is compared for ordinary SNe Ibc and GRB/XRF. Optical data (small dark circles) trace the slowest ejecta to which the bulk of the kinetic energy is coupled while radio and X-ray data (large light circles) trace the fastest ejecta in the explosion. XRF 060218 is an intermediate example that lies between ordinary SNe and GRB with respect to energy coupled to mildly-relativistic material.

Figure 3 (above right): Near-infrared observations of GRB 090423 in the Y-, J-, H-, and K-bands. The dashed red line indicates spectral flux density in the absence of neutral hydrogen absorption at high redshift, while the solid red line includes the effect of absorption at the redshifted wavelength of the Lyman-alpha line. The blue line indicates the effect of dust extinction, which clearly cannot explain the sharp cut-off at about 1.2 microns.

microns) within 20 minutes of the burst. Overlapping with UKIRT, Gemini North began imaging with the Near-Infrared Imager (NIRI) in Y-, J-, and H-bands (see Figure 1) to obtain a photometric redshift estimate which came in between z = 7.6-9.2 (see Figure 3). Subsequent spectra (about 17 hours later) from the European Southern Observatory's Very Large Telescope pegged the burst's redshift at z~8.2, making this the most distant object/event ever detected in the universe (see Figure 4).

At this redshift, GRB 090423 pushes the look-back time to within about 630 million years of the Big Bang, or 4.6 percent of the current age of the universe. Such a constraint brings astronomers ever closer to seeing the first generations of stars and galaxies and leads to a better understanding of star birth within the young galaxies forming in the early universe (see article starting on page 36 of this issue).

The study of short-hard bursts at redshifts between z = 0.5 and 1.2, as well as their affiliation with elliptical galaxies, galaxy clusters, and regions with no ongoing star formation in late-type galaxies, indicates no connection with supernovae for this variety of GRB. Theory suggests that these events are triggered by the collision of compact-object binaries, such as the merger of neutron stars, or even a neutron star and a black hole. Progenitors for the short-duration GRB have a typical age of about four billion years and have a wide range of redshifts. Gemini Multi-Object Spectrograph optical observations, complemented by data from other observatories, show that jets may be involved in short-duration GRB. Energies are also significantly higher than initially thought, and in at least 50 percent of short-hard GRB the energies overlap that of some long-duration GRB (see Figure 5). Illustrative of this is the well-studied GRB 051221a, which has a redshift of z=0.546 (about 10 billion light-years away) and a total energy output 10 times larger than that of previous short-duration GRB. If current trends continue, perhaps the boundaries between the energies and redshifts associated with long- and short-duration GRB will continue to blur. And what might be the fate of the fine line separating long-duration GRB and nearby supernovae? These questions (and likely many we cannot even imagine) will keep astronomers rapidly pointing the Gemini telescopes to the faint afterglows of GRB Targets of Opportunity and probing the very depths of the observable universe.

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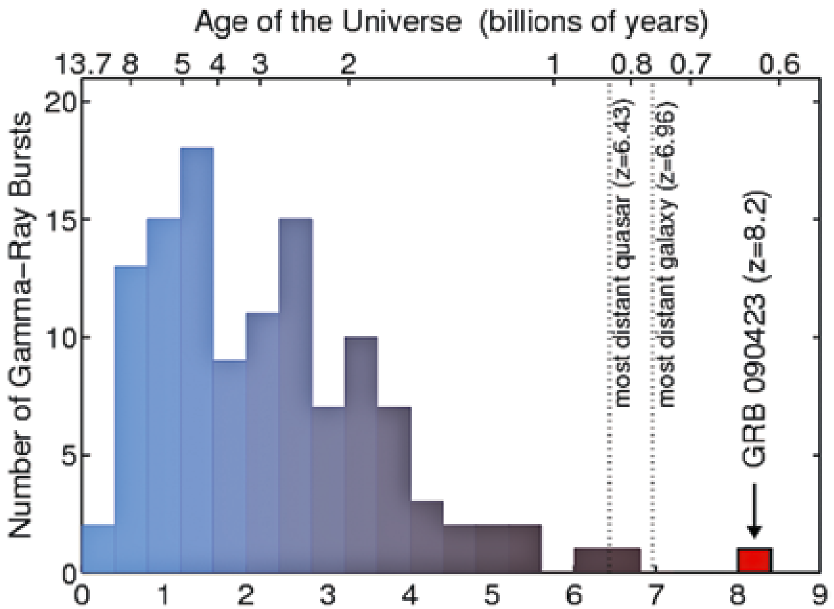


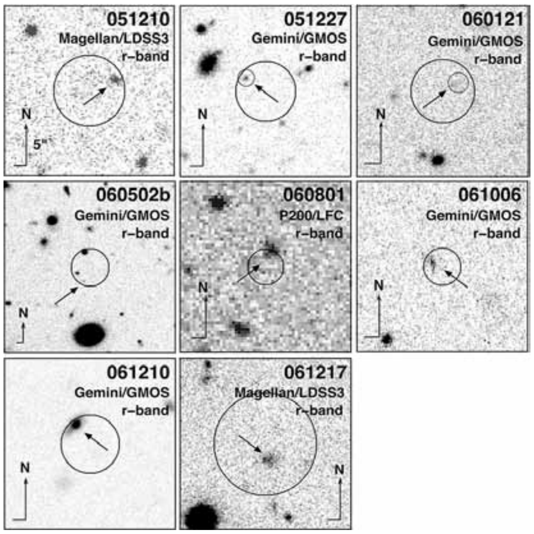


Figure 4: (left, top), Redshift distribution of Gamma-ray Bursts, including the record-breaking GRB 090423 at z = 8.2. Also shown are the highest redshift galaxy (z = 6.96) and quasar (z = 6.43).

Figure 5: (right, top), Images from Gemini and other facilities of several faint short-hard GRB hosts that reside at higher redshifts than previously expected (z~0.5-1.2). The large circles mark the X-ray positions of the afterglows (< 5 arcsecond radius). Arrows mark the positions of the hosts. The higher redshifts lead to a wide range in energy release for short GRB and to a typical progenitor age of a few billion years.

Background on Gamma-ray Bursts:

Gamma-ray Bursts (GRB) are among the most energetic explosions in the universe. Known since 1967 GRB were first detected serendipitously by the *Vela* military spacecraft which was built and launched to detect man-made nuclear explosions in the upper atmosphere or in near-Earth space. Thirty years later, in 1997, it became clear that their origins were associated with very energetic, rapidly occurring events happening in distant galaxies. To systematically identify these transient events, the *Burst Alert Telescope (BAT)* was launched on NASA's *Swift* satellite in 2004, resulting in significantly better detection and follow-up rates for GRB by ground-based telescopes like Gemini. There are two classes of GRB: the long-soft bursts (or long-duration bursts, with "softer" lower energy emissions, surmized to be associated with the death of some massive stars), and the short-hard bursts, (or short-duration bursts, of shorter duration with "harder" higher-energy emissions and thought to be the catastrophic energy output of the explosive merging of massive stellar remnants, like neutron stars or black holes).

Breaking the Operational Mold

Anyone involved in Gemini for at least the past 10 years can appreciate the profound changes in the observatory that have occurred between the onset of our first decade and the opening of our second. However, like trying to see the growth of a child from one day to the next, the evolution of a young observatory isn't noticeable until you look back over many years. Then the transformation appears nothing short of remarkable.

Nowhere is this more obvious than in the revolutionary operational model established at the twin Gemini telescopes. In the following pages, observatory operations are presented in a broad context that sometimes goes beyond the nightly routines on the mountaintops in Hawai'i and Chile. In addition to featuring a sampling of the most significant operational milestones as they relate to Gemini's core scientific goals, this article features several day-to-day operational accomplishments that allow Gemini to function smoothly as a multi-faceted organization. All of these operational achievements ultimately support the science that Gemini does. But they also go beyond it in ways that may surprise you.

Queue Scheduling

For generations, ground-based astronomers were arguably the most pragmatic of scientists because of a simple fact of life: the weather gives, but it can also take away. The stories of weathered-out observations are the stuff of astronomical legend, or maybe even observational "war stories."

From the very outset, planners resolved that at least a portion of Gemini's operations would be queue-based. In this scenario, a list (or queue) of observing programs based on scientific priority is established. Then, in the operation of the queue, each program's observations are made when the conditions are right. In this mode, the whims of the weather largely become irrelevant and averaged-out over an entire semester rather than affecting individual programs. Operating in this mode makes a lot of sense: the space-based and longer-wavelength observatories have always done it, so why not use a similar approach in the optical/infrared regime at Gemini?

Jump to 2010 and look at how Gemini operates, and it's obvious that queue scheduling is now well-proven for ground-based optical/infrared astronomy. Currently over 90 percent of Gemini's user community takes advantage of it, and the demand for "classical time" is rapidly becoming a niche market. However, getting to this point wasn't simple. It required a cultural transformation and the reverberations are still being felt.

When Gemini embarked on this path, many were skeptical, thinking the "classical time" mold couldn't be broken.

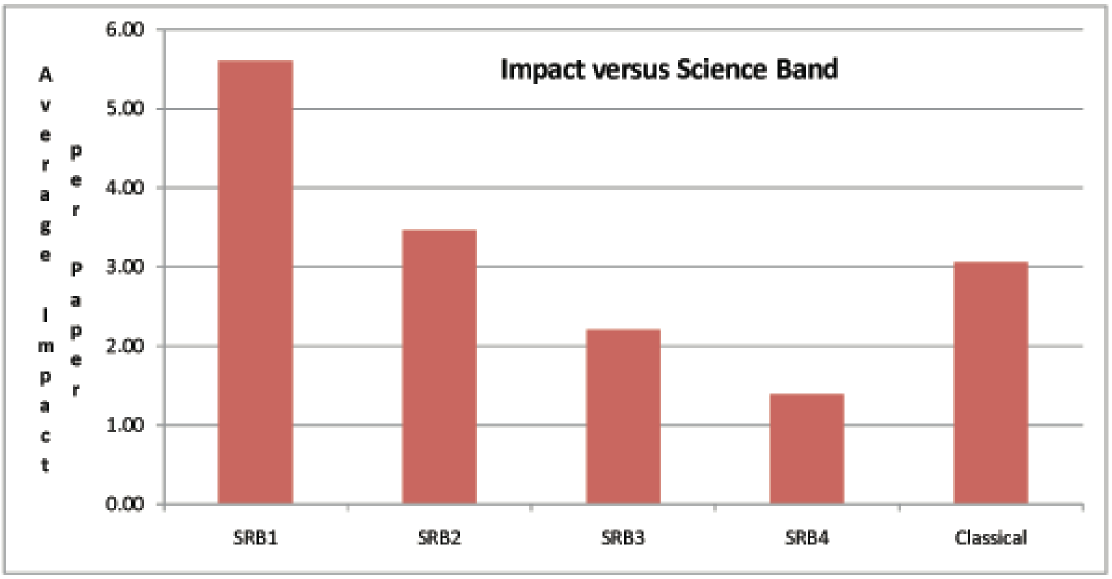


Figure 1: Average impact per paper against the science ranking bands (SRB), showing that higher ranking strongly correlates to scientific impact based on citation rates.

Rick McGonegal, who led Gemini's software group during construction, said in an interview for *Gemini*Focus (see the June 2009 issue, page 40), "Inside the project, a number of us were kind of like, you know, that [queue scheduling] is never going to work (laughs). But, it did. That's the part to me that outperformed it all, because doing that really requires a cultural change [one] that I never thought [we'd] overcome."

Gemini is in an intentionally unique position to take maximum advantage of the queue approach because of the multi-instrument configuration on both telescopes. With up to four instruments available at any given time, observations under almost any Moon phase, atmospheric-water-vapor content, or seeing conditions can be accommodated, making the best use of instrumentation under nearly any circumstance. With the obvious complexity of this system, the queue planning tool (QPT) helps organize the matrix of variables so that the assigned queue coordinator for a given night can make the best decisions to assure maximum on-sky efficiency.

One of the aims of queue scheduling is to ensure that the highest-ranked science programs are completed in preference over lower-ranked programs. Gemini's queue divides science programs into three science ranking bands (SRB) and priority is given to the higher SRB within any set of weather conditions (note that Figure 1 shows four SRB; band 4 is now considered only for bad weather programs that are not charged). Gemini completes approximately 90 percent of the highest-ranked science programs (SRB1) in a given semester—and the data is taken in the conditions required by the program. If these programs were classically scheduled, approximately 35 percent of them would be completed and have all of their data taken in the conditions required.

The big question is whether higher-ranked science programs turn into higher-impact refereed publications. An analysis of Gemini papers published between 2005-2008 shows that, on average, papers from higher-ranked programs do have higher impact (see Figure 1). The data show that Time Allocation Committees rank observing proposals in a manner that results in higher-impact science rising to the top. This also provides strong support to Gemini's approach of giving higher-ranked science programs higher priority to ensure that they are completed.

The bottom-line: Queue scheduling is here to stay at Gemini.

Targets of Opportunity

Among the many advantages of operating primarily in a multi-instrument queue mode is the flexibility it provides when time-critical events happen (like Gamma-ray Bursts, see article starting on page 44) and priorities need to adjust

Figure 2: SSA Erich Wenderoth prepares the telescope for a night of observing at Gemini South.

to accommodate observations of an event. Gemini is uniquely suited for these types of observations, called Targets of Opportunity (ToO), and has developed a reputation for flexibility and success in this area (see article in the June 2007 issue of *Gemini*Focus, page 35).

ToOs are structured as fully-reviewed proposals approved by a time allocation committee for a given semester or semesters. For example, an ongoing program to observe GRB will include available parameters (such as instrument, mode (imaging, spectroscopy), and filters), but will leave out specifics (like coordinates, integration time, etc.), since these variables will depend on the target. Then, if or when an event is detected (i.e. the case of GRB by the *Swift* satellite), Gemini will make the necessary observations. For extremely time-critical observations, the Rapid ToO is enacted, in which current observations are interrupted for turnarounds on the order of 15 minutes. In other cases (like supernovae), where rapid response is not as critical, a standard ToO will ensue, and the queue coordinator will work the observations into the next available queue slot.

For totally unanticipated events (like planetary impacts), a more traditional director's discretionary time (DDT) process is implemented. The ToO program at Gemini is one of the more productive modes, and results include a number of successful programs as highlighted in this issue. See the article, "Monitoring the Solar System" starting on page 8 for an example of how both ToO and DDT time is used effectively at Gemini for time-critical transient event observations.

System Support Associate Model

Traditionally, observatories have staffed nighttime operations using a model based on technicians, called telescope operators, who run the telescope on behalf of visiting astronomers. For many reasons—including those related to Gemini's queue-based operational model and a desire to find a system that allows better retention and opportunities for staff—Gemini has adopted what we call the System Support Associate (SSA) model. This approach includes significantly more than just a title change for the staff members who operate the telescope, subsystems, and instruments each night.

Very few classical observers are at the Gemini telescopes while observations are being made. On most nights, the minimum personnel required to open and operate the telescope are two staff members (SSA and astronomer). Together they execute the nightly plan made out by the queue coordinator (QC) during the day. Extra support is also available at night from the QC if needed, which is mostly done from home. It is the responsibility of the SSA to safely operate all of the physical systems related to the telescope and subsystems while working closely with the staff scientist to acquire

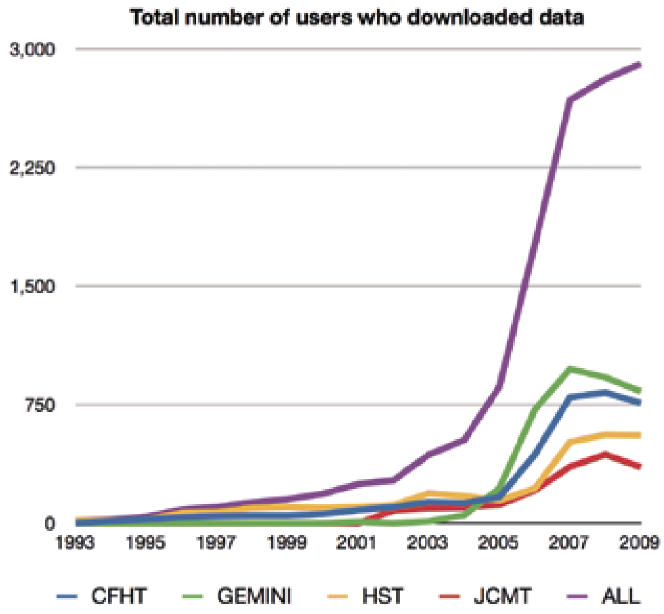


Figure 3: Data downloads by users of the Gemini Science Archive compared to other observatories.

targets, monitor instruments, and remain cognizant of all systems, and of course monitor weather conditions. Gemini Observatory has adopted a model that also allows the SSA to be more involved in daytime and nighttime operations, making the SSA more flexible and cross-trained in areas that allow better telescope coverage. Each SSA works about one five-night shift of operations per month, with the remainder of the monthly work time devoted to other projects at sea level. These projects can include instrument commissioning, instrument calibrations, software testing, scripting, serving as the technical assessment secretary, miscellaneous engineering tasks, and data analysis. This model provides more challenges for the SSA while improving expertise in telescope operations and systems. SSA positions have also led to many new opportunities at Gemini (see article starting on page 98 of this issue by Brain Walls, who began as an SSA and is now a Systems Engineer).

Gemini Science Archive

Like most aspects of science operations, Gemini's emphasis on queue scheduling has a trickle-down effect on other operational elements (see previous sections in this article on Targets of Opportunity and the System Support Associate model). This is especially true for the system established to distribute data to our users. Because none of our users are generally present when their data is obtained in the very dynamic queue mode, it is of paramount importance to make that data available to a principal investigator (PI) quickly and efficiently.

The Gemini Science Archive (GSA) is a system run from the Canadian Astronomy Data Centre (CADC) at the Herzberg Institute of Astrophysics in Victoria, British Columbia. The CADC archives data for a host of astronomical facilities, including Hubble Space Telescope, Canada-France-Hawai'i Telescope, and the James Clerk Maxwell Telescope (among many others), and is also home to the Canadian Virtual Observatory. The arrangement is a model for reciprocal agreements with Gemini's partner countries, bringing the strengths of partner resources to the direct benefit of our users around the globe.

Once a PI's data have been obtained, it is immediately uploaded to the GSA and available "literally within minutes," according to Gemini's Data Analyst Michael Hoenig. At that time, the PI is notified of the data's availability via e-mail so it can also be accessed on the GSA website using a unique ID and password. Generally, the PI has an 18-month proprietary period in which he or she maintains exclusive rights to the data for analysis and publication. See Figure 3 for a comparison of users of the GSA compared to other observatories with data archives.

Figure 4: Participants at the annual Gemini planning meeting.

Planning – An Observatory-wide Process

Given the myriad projects, programs, priorities, and logistics at a state-of-the-art astronomical observatory, the coordination of the resulting complex system is a formidable undertaking. Accustomed to such a challenge, Gemini's systems engineering group spearheaded an initiative aimed at managing both the planning and coordination of the system in an annual observatory-wide process overseen by the Gemini directorate.

In 2007, the primary tool that would power this process was introduced to Gemini managers. Called *Project Insight®*, this web-based software has a highly-customizable interface that, in its most elemental function, matches the work that needs to be done against resources available.

Each year, generally in October, Gemini managers meet in a two-day planning retreat (see Figure 4). In preparation, they assemble and input details (into *Project Insight®*) of planned projects for the next year and beyond. During the retreat, all of the proposals are discussed and weighed against observatory resources and strategic objectives in order to come up with a final list of projects for the next year. In many cases, when resources are depleted, some projects are relegated to a "back burner" for consideration in future years.

In addition to planning, *Project Insight®* is designed to help managers monitor progress at all levels of a project's development, from initiation to completion. From *Gant* scheduling charts to resource allocations and availability, the project monitoring has become a unified process at Gemini and provides a common language, process, and culture for looking ahead.

Stewards of our Planet

As an astronomical observatory we know first-hand that Earth-like planets are hard to find. Until we have the means to discover and travel to other hospitable planets, we'll need to take good care of the one we live on. To this end, Gemini has adopted an institutional philosophy to minimize our impact on the environment at many levels, from recycling to energy conservation.

A critical area where Gemini can have the greatest impact is in the area of energy conservation. For example, the summit facilities consume 70-80 percent of the observatory's total energy usage. Experiments are ongoing to find ways to optimize the daily cycle of cooling the interiors of the domes to balance the expected nighttime temperatures

Figure 5: (above left), Cyclists like astronomer Rachel Mason appreciates that Gemini has bike racks at both the North and South Base Facilities.

Figure 6: (right), Facilities Specialist David Moe sorts the recyclables at the Hilo Base Facility.

for optimal "dome seeing." While testing is ongoing, this has the potential to produce a significant impact on overall observatory energy usage. A more immediate impact is the replacement of older, less-efficient compressors for base-level air conditioning. Compounding with that is the timing of building cooling to match diurnal cycles of solar warming and building occupancy.

Related to Gemini's energy usage is staff travel. Traditionally, Gemini has encouraged frequent in-person interactions between staff at the two sites. An effort is ongoing to balance that with energy conservation by better utilizing alternate means of interaction, such as upgrading multi-point videoconferencing infrastructure allowing meetings with a dozen or more separate nodes. Already in 2009, staff travel has been reduced by 23 percent and shrunk Gemini's overall air travel energy "footprint" significantly.

Ultimately, the only way a program like this can succeed is if staff members embrace it. Since its inception, staff are participating at multiple levels, from sharing conservation ideas on an internal "Greening Gemini" blog, to using bike racks provided to encourage alternate transportation. Recycling and the use of washable kitchenware are all part of the Gemini solution for keeping our planet healthy—even if we do find another Earth-like planet.

For more information on how Gemini is treading lightly on our planet, see pages 62-66 in the December 2009 issue of *Gemini*Focus.

Keeping Gemini Ticking: Engineering & Technology at Gemini

The more you understand about what makes an astronomical observatory like Gemini "tick," the more you appreciate having a top-notch engineering team behind the science. From attending to the nuts and bolts that make up the observatory's physical structures, to the more virtual elements like software packages, Gemini's engineering team is as important as clear, dry, photometric skies when it comes to running a successful observatory.

Supporting Gemini is a constant battle with entropy (maintenance). Although this function may not seem as glamorous as finding planets around other stars, the latter couldn't happen without the former. Like an athlete's seemingly effortless performance, a common theme among Gemini engineers is that their hard work shouldn't be noticed — a smoothly operating and integrated telescope system is the main goal. However, when one looks back at the past decade at Gemini, the engineering group has made uncountable contributions that go far beyond what has become the assumption of a smoothly operating telescope. This article highlights a few of the most significant milestones and how they impact the present and future of our twin telescopes.

First, Some Philosophy...

Applying Gemini's "Two Telescopes, One Observatory" approach is more than just words within Gemini's engineering group, it's a philosophy that fosters success. Even before Gemini began science operations, engineers from both the north and south broke down any possible geographical and cultural barriers, as well as personal boundaries as staff "commuted" between Chile and Hawai'i. "The very first time my family traveled to another country was to Hawai'i," says Gemini's Associate Director of Engineering/Chief Engineer Gustavo Arriagada. "When I became a Gemini employee, the conditions of the contract specified a relocation to Hawai'i for two years to work on the construction of the Gemini North telescope. Since then, I have traveled between the two sites at least four times per year."

This attitude toward, and strong connection between, the two telescopes, established early on among the engineering groups, survives to this day in the standardization of processes, reports, change/version controls, planning, and configurations between Gemini North and South. This mindset is nowhere more obvious than in the relationship between engineers and the instrumentation group, where the integration of complex systems must meld seamlessly into, and onto, the telescopes. From software to an instrument's mass distribution, a "systems engineering" approach permeates both Gemini sites, bringing corporate-style efficiency and attitude for success to every project. "When I became chief engineer," says Arriagada, "one of the highest priorities in my five-year plan was to assemble a strong systems engineering group focused on supporting and promoting the best engineering practices with a clear emphasis on a corporate approach."

Figure 1: Claudio Araya (background), and Hector Figueroa (foreground) apply absorbent tissues during the stripping process of the Gemini South mirror. The recoating of a Gemini primary mirror requires about 11,000 person-hours in preparations and over 3,000 for the actual coating process.

How to Engineer a Silver Lining

Very early in the planning stages, Gemini set one of its most ambitious goals: to contribute to Gemini's exceptional infrared performance by developing an on-site facility to coat the Gemini mirrors with protective silver. Its characteristics in the infrared make silver the obvious choice for an infrared-optimized telescope. While most of the work for both Gemini coating chambers was contracted for "turnkey" delivery, the reality was that the engineering/optics groups spent countless hours reconfiguring and even redesigning the system to work as planned. Furthermore, much testing remained on the best formula for a multi-layer sputtered coating that could survive the harsh mountain environment. With much of the work completed by 2004, a silver coating was applied to the Gemini South mirror in May 2004, followed in November by the same process at Gemini North. In the end, the coatings met or exceeded the stringent reflection and emissivity specifications set by Gemini's early visionaries. Perhaps even more remarkable, over the years, the coatings have significantly outlasted the original lifetime prediction of two years.

Figure 2: (above left), Gemini North during propagation of the laser guide star sodium laser with a backdrop of the summer Milky Way. The glow of Hilo is to the left and evening twilight to the right.

Figure 3: (above right), Composite Altair-LGS NIRI (H- and K-bands) and HST WFPC2 (V- and I-bands) of Arp 299. The field-of-view is almost 50 arcseconds across.

"Initially there was a lot of doubt that we could produce a protected silver coating that would maintain its optical reflectivity while sustaining low thermal emissivity over several years," says Gemini's Optical Group Leader Maxime Boccas. "Looking back over the past decade, we can be proud of what the optics and engineering groups have achieved. It's a real accomplishment for thin-film and astronomical communities!"

Emissivity, or the amount of thermal radiation emitted by the surface of a telescope's mirror, is a bane to ground-based, mid-infrared astronomy. Gemini's goal to bring the total telescope system's emissivity to unheard of levels (below four percent) was once considered very ambitious. Today, emissivity levels are routinely measured at about four percent throughout most of a silver coating's life on the Gemini mirrors.

To maintain a coating's high performance, Gemini's engineers perform a weekly carbon-dioxide "snow" cleaning to remove any accumulated dust. In addition, a unique *in-situ* wash provides a thorough liquid cleaning about every six months.

The Gemini coating process has proven so successful that it has recently been used (for the second time) on the aluminum coating of the SOAR mirror at Cerro Pachón (see article on page 98 of this issue). Gemini's process has also resulted in numerous scientific papers, conference presentations, and interest by other observatories desiring optimal mid-infrared performance.

Laser Guide Stars

The release of Gemini's first data set—adaptive-optics (AO) images of the Galactic Center of the Milky Way (see page 6)—heralded the use of AO technology at Gemini. Adaptive optics significantly reduces atmospheric blurring of images, and is an established mainstay in much of Gemini's science. However, due to the limited number of natural guide stars close enough to astronomical targets that are bright enough to adequately sample turbulence in the atmosphere, laser guide stars (LGSs) are now also a staple of 8- to 10-meter-class telescopes.

Mounting and propagating a 10+-watt sodium laser is not a trivial matter. First, there is the issue of mounting the laser on a stable platform within a stable enclosure. In the case of Gemini North, the laser is about the size and mass of an upright piano; the more powerful 50-watt laser recently delivered to Gemini South is described in an article starting on page 93 of this issue). Then, the laser's light must be directed through relay optics from the side of the telescope to the laser launch telescope (LLT) behind the secondary mirror.

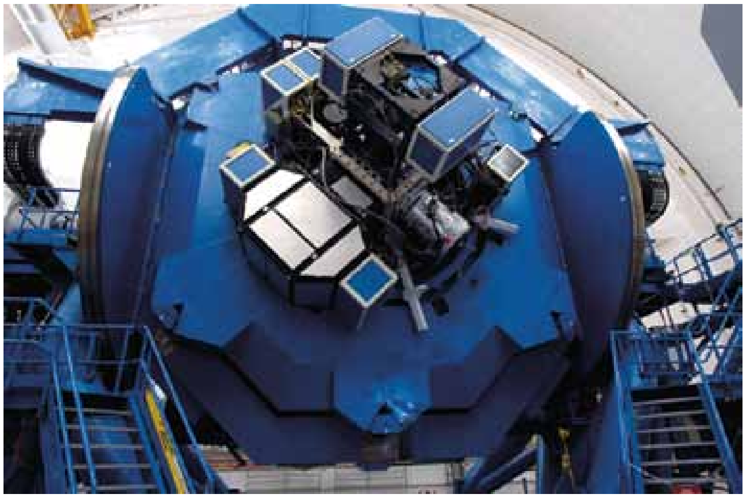


Figure 4: (above left), Gemini North instrument cluster.
Figure 5: (above right), Gemini South instrument cluster.

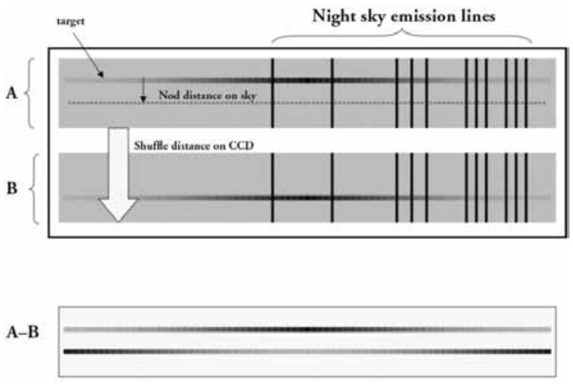
The LLT is also a large installation. Its job is to propagate the laser's light into the sky, while precisely tweaking its direction so that the laser light "anticipates" how the atmosphere will shift its position in the sky. These shifts are called "tip-tilt," and this can be sampled with a nearby star that can be relatively dim compared to the star required for higher-order AO corrections. When the laser light reaches an altitude of about 90 kilometers, it excites naturally occurring sodium atoms (deposited by meteors when they burn up in the upper atmosphere) and causes them to glow, producing a point source of light. This laser guide star is then used by the AO system to sample atmospheric turbulence, or wavefront distortions to light, so that a rapidly deforming mirror can "unbend" the starlight and deliver very high-resolution near-infrared images to the instrument's focus.

However, that's only the tip of the LGS technical/logistical iceberg. In order to propagate a laser into the night sky, military and aircraft control agencies must be notified in advance. A system (or people) must also be in place, to track and shut down the laser in the unlikely event that an aircraft were to fly into its beam (to date, this has never even come close to happening). Add to this the significant level of technical maintenance required of even the Gemini solid-state laser, and you begin to appreciate the magnitude of the engineering effort needed to make the system work. But it does, and because of this Gemini can provide users with near-diffraction-limited images in the near-infrared over a significant fraction of the sky, and produce data like that seen in figure 3.

Supporting the Queue

Possibly the most concentrated collection of technology of any telescope in the world is situated at the Cassegrain focus of both Gemini telescopes (see figures 4 & 5). Here, clustered on the instrument support structure (ISS), is about ten tons of instrumentation, along with instrument "switching" optics, cryogenics, fiber optics, power cables, and heat transfer lines. To compound to the complexity, all of this must turn to compensate for field rotation as the telescope tracks on the sky.

For the most efficient operation of the queue (see page 48) it is critical that most or all of the instruments mounted on the ISS are aggressively maintained and operational for nighttime use. According to Bernadette Rodgers, head of science operations at Gemini South, "The high rate of completion of queue programs at Gemini depends critically on our ability to switch between instruments rapidly and efficiently during the night. Being able to change instruments in the time it takes to slew to a target—in response to changing weather conditions, program priority, or a sudden Target of Opportunity trigger—is essential to the efficiency and productivity of the queue."



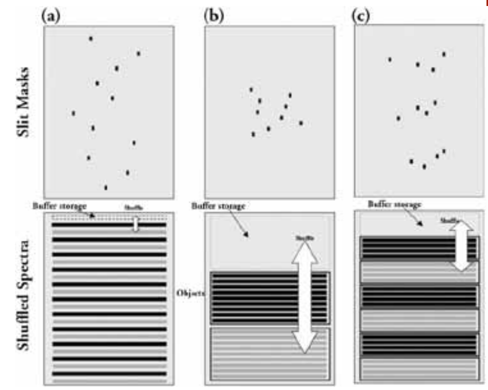


Figure 6: (above left), Schematic of Nod & Shuffle for a single slit. When the telescope is in the "object" position, CCD area "A" records a spectrum. The "sky" position records the nodded spectrum (in this case the telescope has been nodded a few arcseconds along the slit direction). The area "B" is non-illuminated by the mask and serves as a storage area for the spectrum for subsequent extraction.

Figure 7: (above right), Illustration of masks with different shuffle distances. The top row shows the input masks, and the bottom row shows the resulting shuffled object-sky spectra. The black spectra correspond to image A in Figure 6, and the light grey spectra correspond to image B in the same figure; (a) a mask where the shuffle is only a few pixels, and the sky is stored below the object – appropriate for extended, relatively low-source-density regions. (b) a mask where the shuffle is large, appropriate for cases with compact regions of high-source density, and (c) an intermediate case. This compromise has the advantage of allowing a high-density extended field to be tacked while minimizing the number of object-storage interfaces where it is necessary to leave gaps. Note that in reality the area we have shown as a single "detector" is three CCDs (in GMOS, these are arranged left to right).

Nod & Shuffle

One of the early milestones that propelled Gemini to the forefront of deep optical spectroscopy is the successful removal of interference from natural light emitted by the sky. Gemini accomplished this by employing a technique called Nod & Shuffle (N & S). The idea is to alternately collect light from an astronomical target's spectrum and then collect some from an adjacent empty part of the sky so the sky's naturally occurring luminescent glow can be subtracted out. Meanwhile, the charge accumulated by the light-sensitive CCD shuffles to an adjacent storage area to accommodate the transaction (see Figures 6 & 7).

The integration of N & S at Gemini demonstrates the close collaboration between the engineering and science groups. Advanced, unique capabilities like N & S require a wide range of disciplines to be successfully integrated into all of the observatory's opto-mechanical and software systems. The resulting application of this technique is described in the article on page 40 of this issue, which features the extremely successful Gemini Deep Deep Survey. Although other smaller telescopes (including the 6.5-meter Magellan telescopes) offer this capability, Gemini is still (as of April 2010) the only 8- to 10-meter-class telescope to make it available to our users.

Observatory Software Systems and User Software

The software developers are often the "unsung heros" of any observatory. They create the virtual glue that literally binds all of our facility's technologies into one coherent system. Like many of our engineering efforts, software development has been underway at Gemini since even before the first shovel broke ground on Mauna Kea's cinder-covered surface. Over the years, the observatory's telescopes, enclosures, instrument controls, safety interlocks, data pipelines, queue planning tool, and even the semi-automated observing log have the software group's collective fingerprints all over them. This team's accomplishments are often so transparent that they are embedded in our institutional subconsciousness. But, each sunset, when the night crew arrives and starts another night of observing, the observatory's operation and efficiency depend on these millions of lines of code all working together seamlessly.

To accomplish this, close coordination between the users (system support associates (SSAs) and scientists) and the software developers is essential. When our users see the software face of Gemini, it is usually with the Phase I and II Observing Tools. Prompted by Gemini's queue scheduling model, creating a way for users to define a program to the specificity needed to execute the observation accurately presents a unique challenge. The Gemini solution has provided our broader observatory community with a framework that has proven to be extremely useful and has been adopted and improved repeatedly at other facilities.

Figure 8: Participants from the Earthquake Readiness Workshop held in Chile in early December of 2007.

The next point at which users rely on Gemini software again is in the data-processing tools for such tasks as reducing Nod & Shuffle data, creating datacubes from integral field unit (IFU) observations and simply calibrating with flat fields. Traditionally, this has been done using the Image Reduction and Analysis Facility (IRAF) where the Gemini package now contains over 200 individual scripts. Porting these over to a Python-based package called PyRAF is already underway at Gemini.

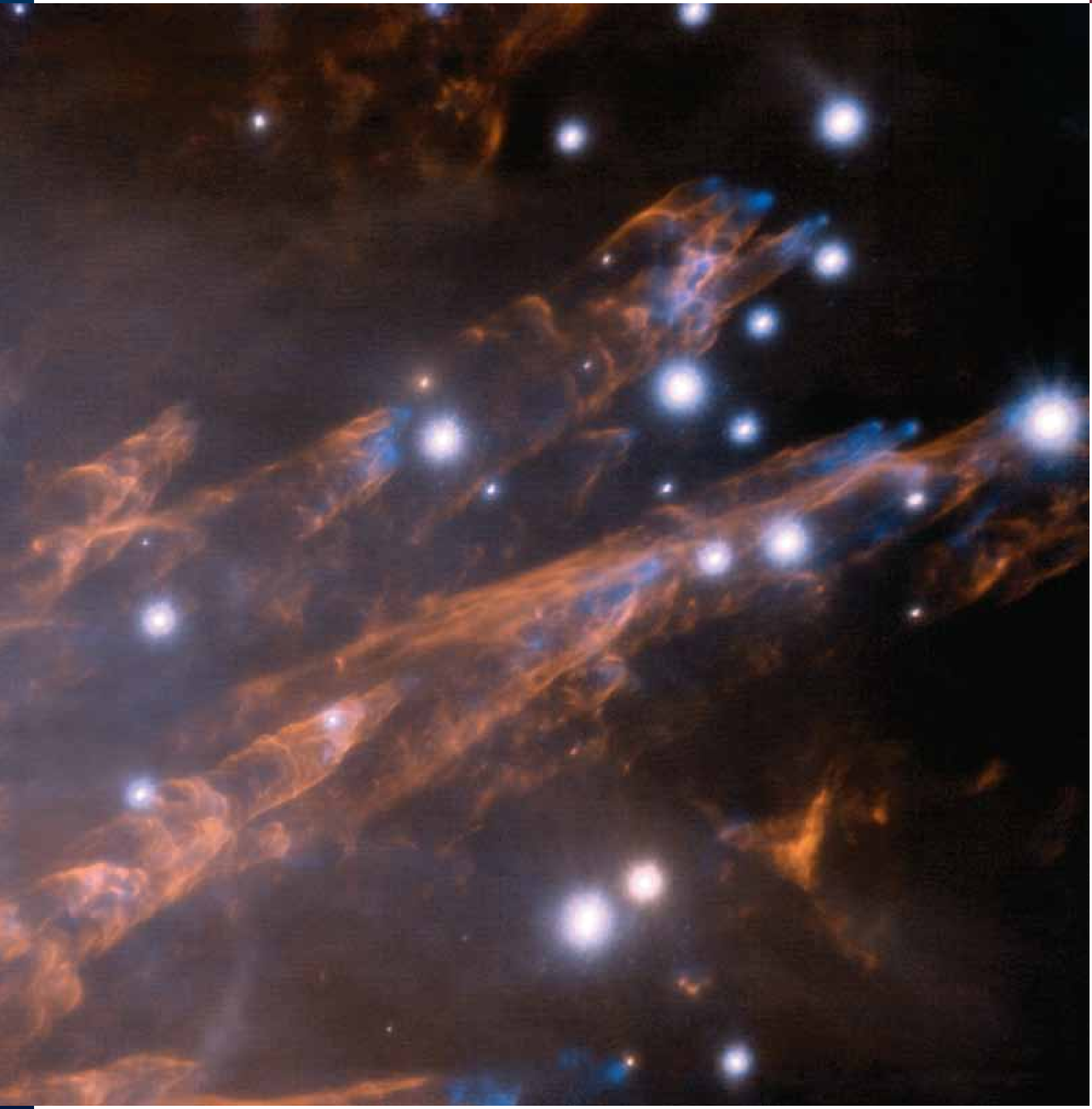
Moving into the next epoch of software at Gemini will bring a continued emphasis on remote and automated operations and data processing. As has always been the case, Gemini will do this with healthy critical input from our users so that Gemini data, from start to finish is easy to use and work with.

Natural Disaster and Emergency Preparedness

On the morning of October 15, 2006, Gemini North (and much of Hawai'i) was jolted into awareness of our vulnerability to Earth's natural forces when a magnitude 6.7 earthquake struck the Big Island. This was the first time that either Gemini telescope suffered appreciable damage due to an act of nature, and it made all of the observatories on Mauna Kea (and around the world) reconsider how prepared astronomers are for events like this.

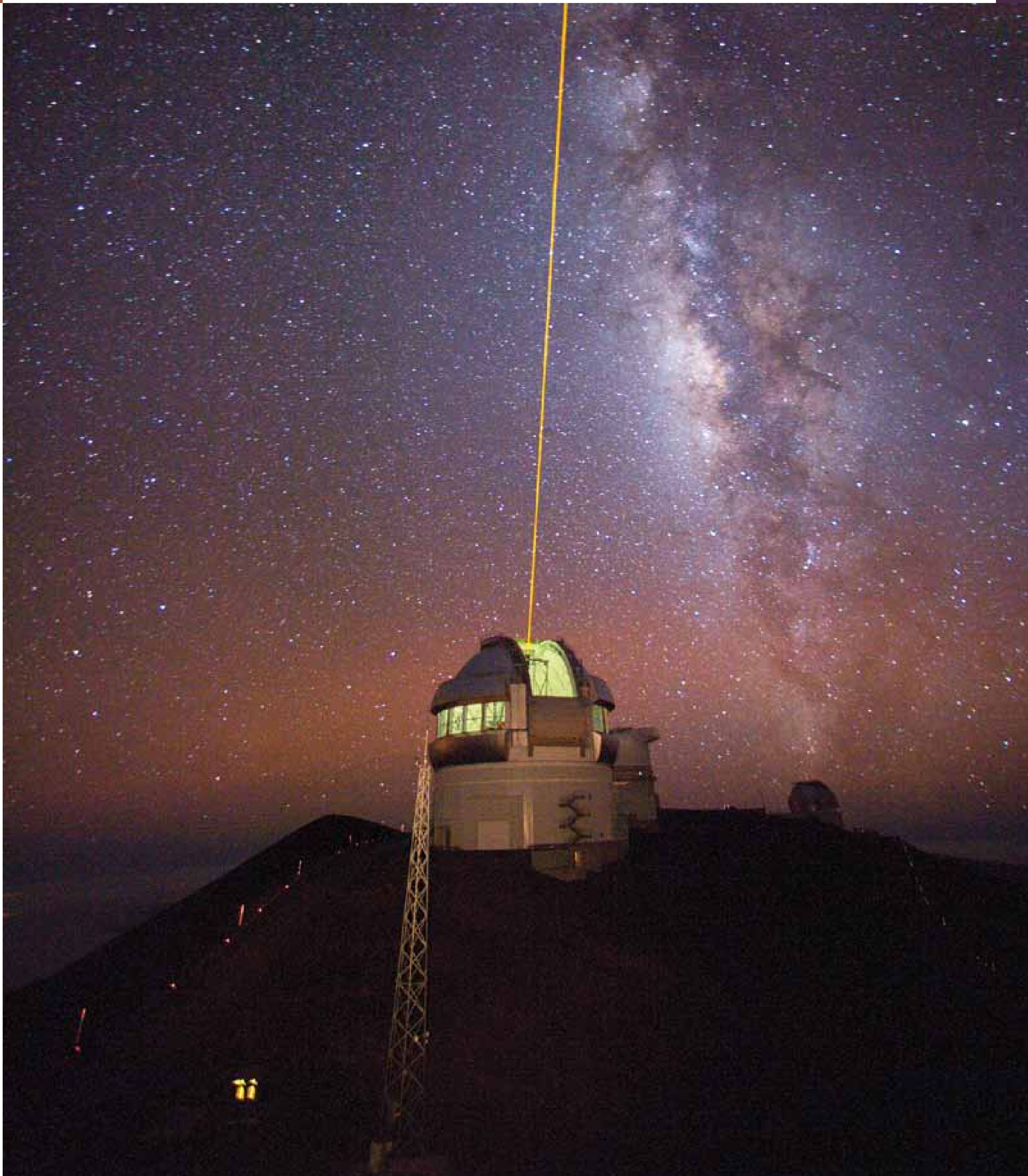
Immediately after the earthquake, Gemini began a major effort to assess the damage and move the Gemini North telescope back into full operations as quickly as possible. In the end, the observatory lost 26 nights before the telescope was back on the sky doing science. The real, long-term impact of this event was to raise awareness of the risks of natural disasters to our facilities and to increase preparations so that when events of this magnitude (or greater) occur, we will be even better prepared and subsequent recovery efforts will be easier. The February 2010 major earthquake in Chile (and the continuing aftershocks) reminded us again of how vulnerable both facilities are to such natural disasters although this one had little effect on Gemini South.

To address this issue, the Gemini engineering group played an instrumental role in organizing a special March 2007 workshop that engaged all of the Mauna Kea observatories. During the meeting, we identified areas of weakness such as electrical grid access, as well as areas where common planning, communications, and support are appropriate (see article in June 2007 issue of *Gemini*Focus pages 49-51). In addition to this meeting, a Chilean version called the Earthquake Readiness Workshop was held in December of the same year (see Figure 8). It brought together representatives from most of the existing and planned observatory facilities in Chile (see article in the June 2008 issue of *Gemini*Focus pages 49-51). Both of these meetings were organized by Gemini and will leave a legacy for the engineering of complex instrumentation in seismically active regions.



The images collected here are a fitting end to this special section on Gemini's first ten years of science. The editors asked Gemini staff to pick their favorites from the Legacy Images collection. Two of the top favorites – Jupiter with "Red Spot Junior" and Saturn with Titan are shown on pages 8 and 9.

Orion *Bullets*



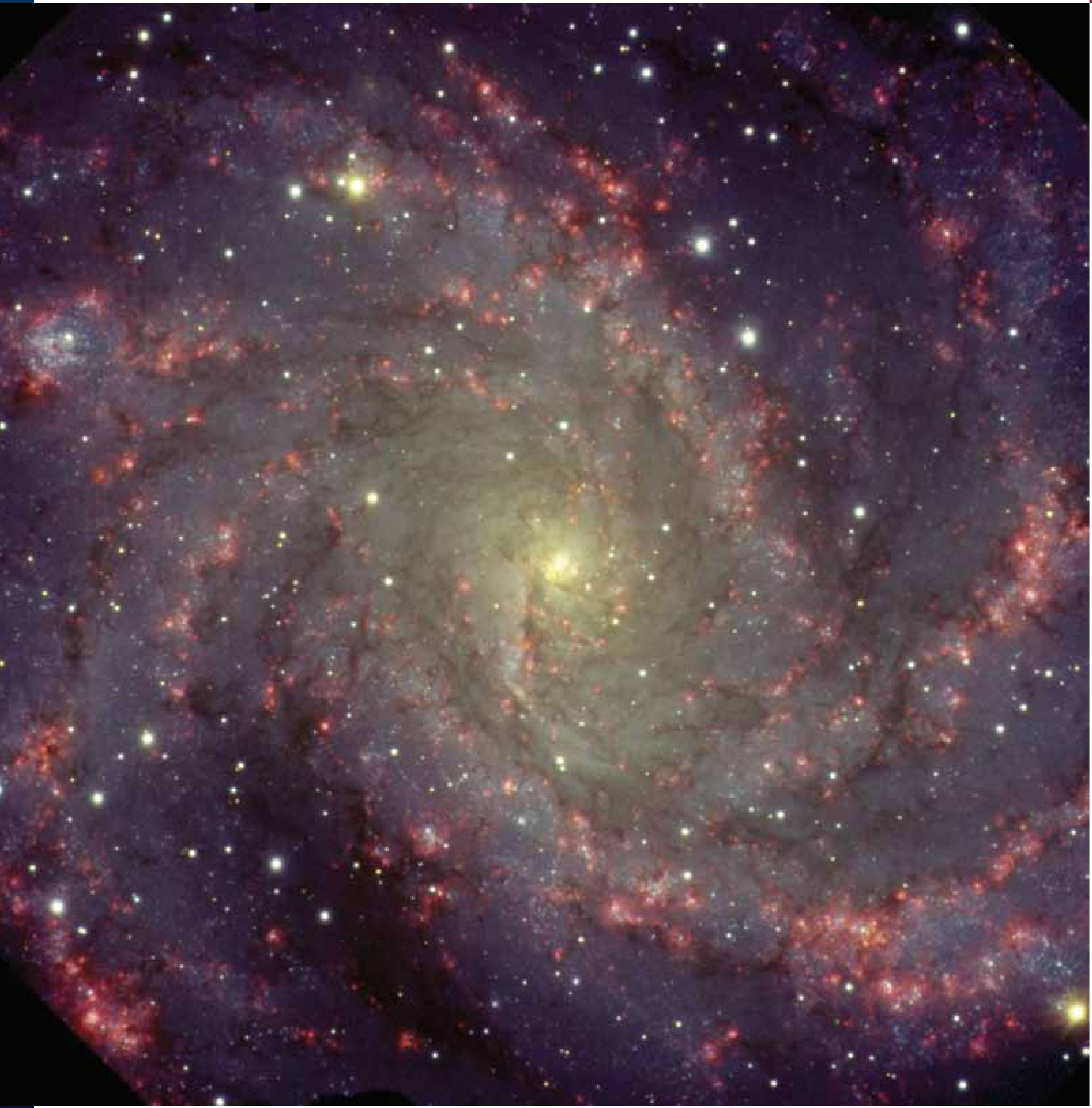
Gemini North Laser Guide Star (LGS)

M74 *Perfect Spiral*

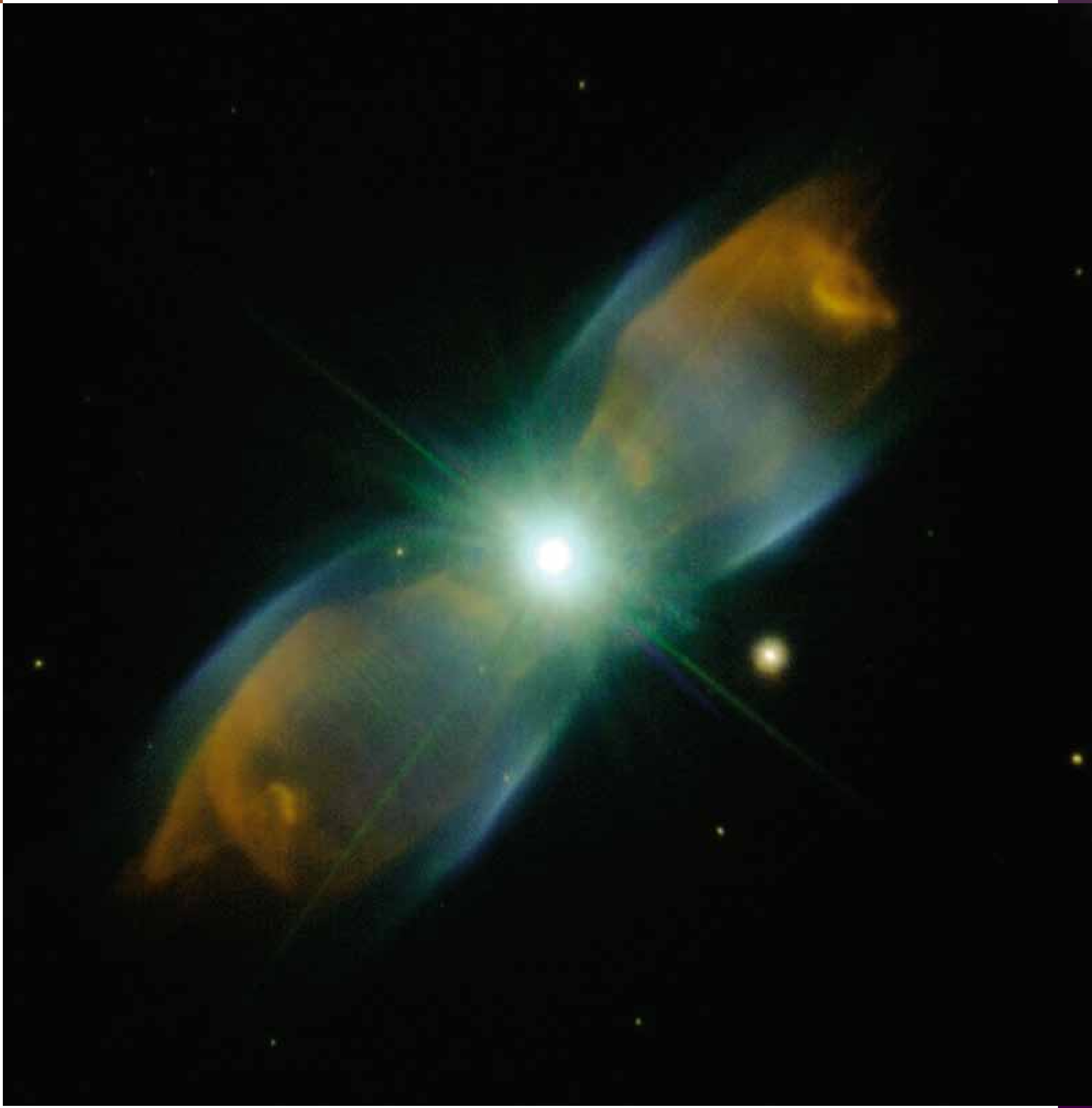
NGC 5426-27

M20 Trifid Nebula

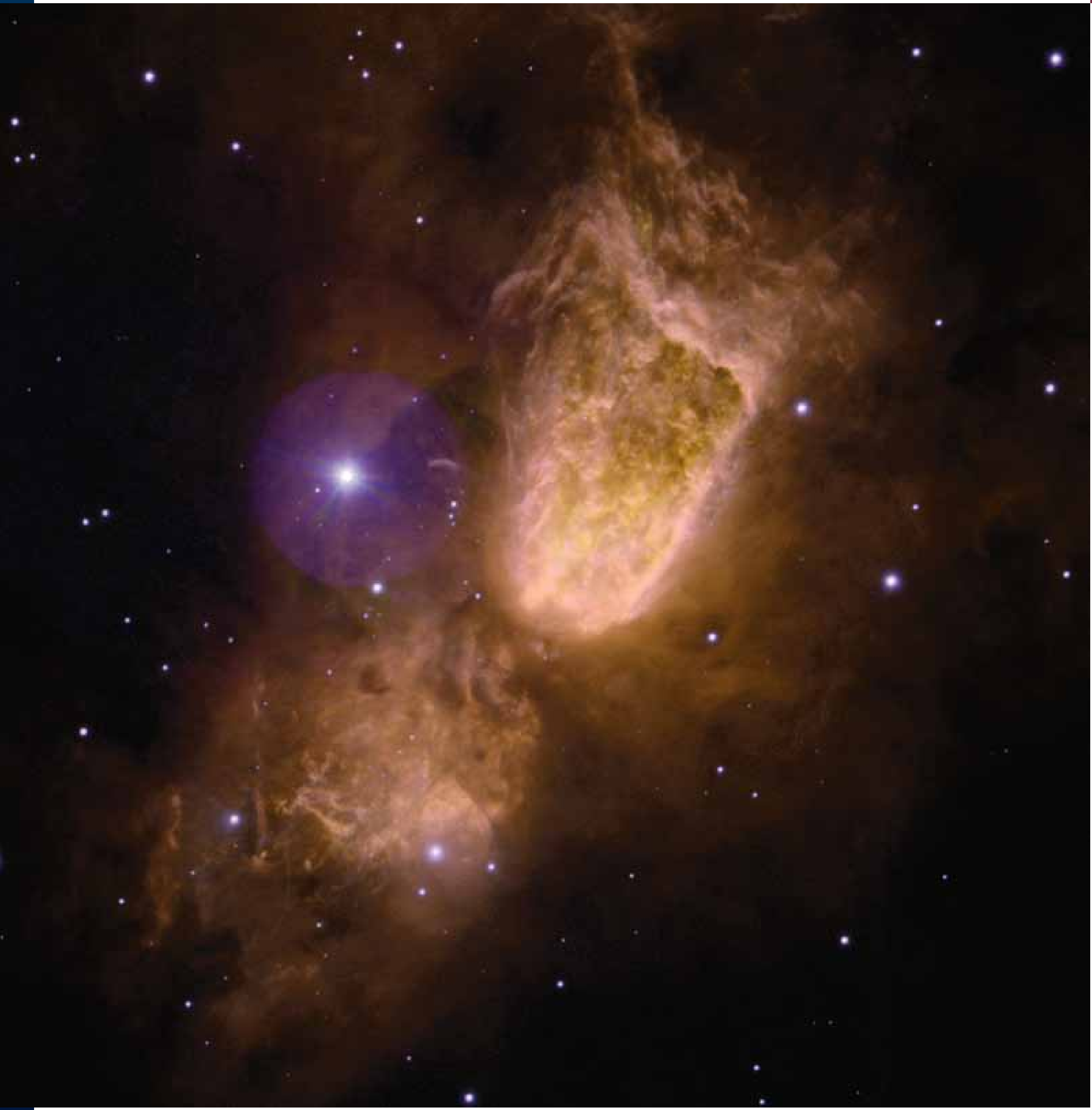
DEM1316



NGC 6946



M2-9



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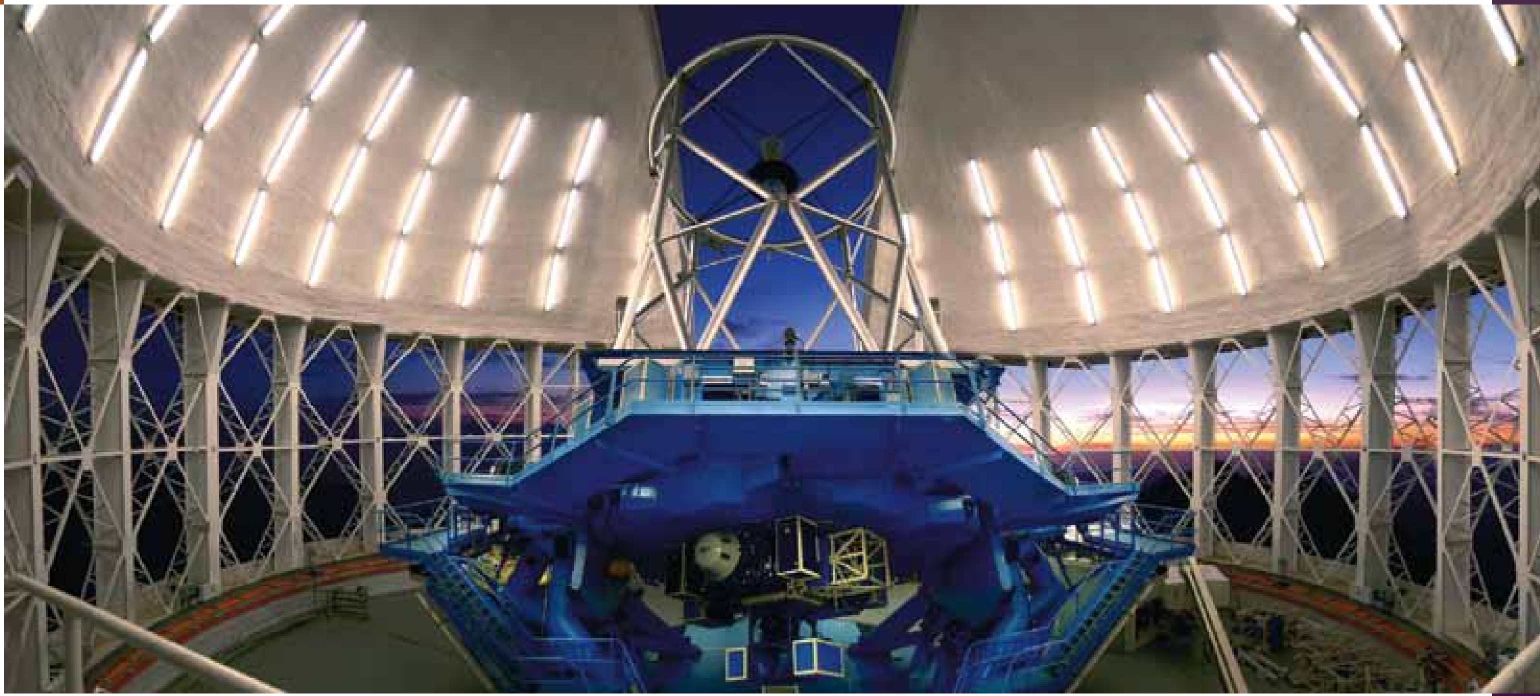

Gemini South Telescope

by David Alexander

Energetic Galaxy-wide Outflow in a Distant Quasar

Modern-day cosmology is a rich cocktail of observations and theory, and nowhere is this more true than in the study of galaxy formation and evolution. Hard observational constraints guide our theoretical models. Those models provide highly detailed insights into the potential physical mechanisms that drive the growth of galaxies along with their massive central black holes.

One area where these theoretical models have been particularly successful is in highlighting that star formation must have been truncated in the most massive galaxies at high redshifts ($z \sim 2$-3, when the universe was about 3 billion years old or about 25 percent of its current age). The leading candidate processes that are thought to cause this truncation are galaxy-wide outflows and winds that are associated with either star-formation activity, energetic winds from nearby supernovae, or active galactic nuclei (AGN; e.g., winds and jets initiated from the black-hole accretion disk). If they are energetic enough, these winds could heat the cool galactic gas and/or eject it from the gravitational potential of the host galaxy, effectively turning off any further significant star formation.

Integral field units (IFUs) are the ideal tool for identifying galaxy-wide energetic outflows because they provide spectro-imaging covering several arcsecond fields of view. The typical expected signature of an outflow region contains broad emission-line gas components kinematically distinct from the narrow emission-line gas in the host galaxy (with velocity offsets of several hundreds of kilometers per second) that is extended over kiloparsec scales.

IFU observations of the [OIII] (rest-frame 5007 Ångstroms) emission in a handful of massive radio-loud AGN at $z \sim 2$-3 have indeed revealed the signatures of galaxy-scale energetic outflows. The outflows from these systems appear to be driven by radio jets, initiated by AGN activity. While the IFU data provide evidence that energetic outflows can be identified in distant galaxies, radio-loud AGN are rare beasts, and it is far

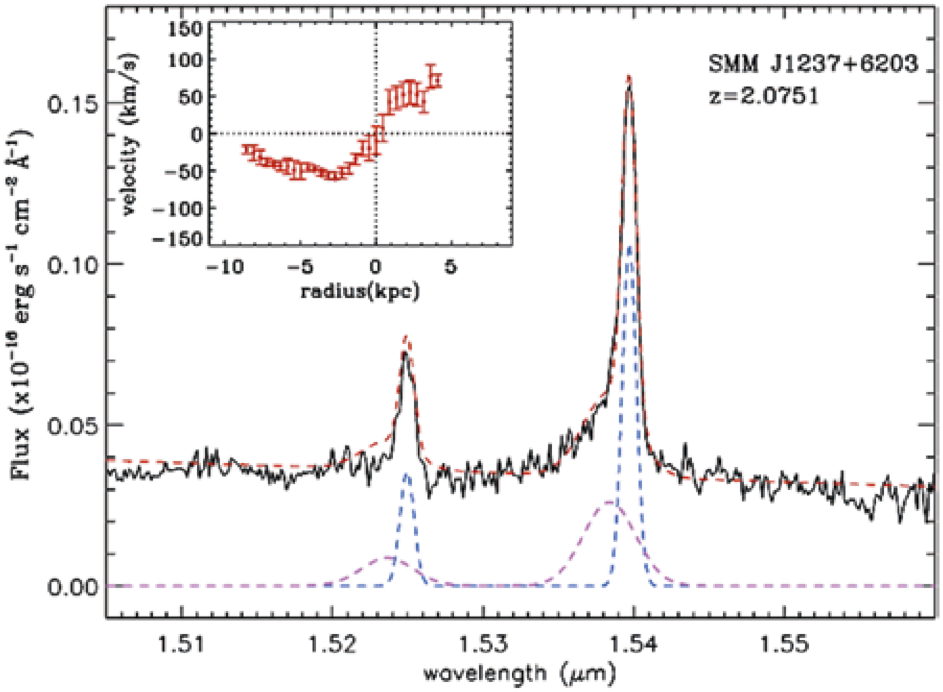

Figure 1. *Collapsed one-dimensional NIFS spectrum showing the emission-line profiles fitted with both a broad and narrow emission-line component. Inset plot shows the narrow [OIII] velocity field.*

from clear how common these outflows are in the typical distant massive galaxy population. To throw light on whether outflows are ubiquitous in the distant universe, we used the Gemini Near-infrared Integral Field Spectrograph's (NIFS) IFU to search for galaxy-wide energetic outflows in more typical radio-quiet systems. In this summary, we present our initial results from this program on the $z \sim 2$ radio-quiet quasar SMM J1237+6203.

SMM J1237+6203 is an optically bright $z = 2.07$ quasar that is also bright at submillimeter (850 μm), radio (1.4 GHz), and x-ray (0.5-8 keV) wavelengths. The estimated infrared luminosity of SMM J1237+6203 is of order 6×10^{12} solar luminosities, indicating that it is a distant ultra-luminous infrared quasar. The AGN in SMM J1237+6203 is luminous (x-ray luminosity ~ 10^{44} ergs per second) and undoubtedly contributes to a considerable fraction of the infrared luminosity.

However, given the bright submillimeter and radio emission, it seems likely that SMM J1237+6203 also hosts an ultra-luminous infrared starburst in addition to the luminous AGN. Previously published near-infrared spectroscopy shows that SMM J1237+6203 has bright, and possibly broad and extended, [OIII] emission. These are the expected signatures of a galaxy-wide outflow, although high-quality IFU observations are required to provide confirmation and more detailed constraints.

Gemini NIFS IFU Observations

We obtained the NIFS IFU observations of SMM J1237+6203 on May 22 and 30, 2008, with a total on-source integration time of 7,800 seconds (thirteen 600-second individual exposures obtained in a standard ABBA configuration). The observations were taken in excellent photometric conditions with ~ 0.3 arcsecond seeing. The NIFS IFU uses an image slicer to take a 3×3 arcseconds field (with a pixel scale of 0.05 arcsecond) and divide it into 29 slices of 0.103 arcsecond width.

The collapsed one-dimensional spectrum is shown in Figure 1. The [OIII] emission line has a blue asymmetric profile, which is fitted with two underlying Gaussian profiles: the offset between the narrow emission line (FWHM ~ 210 kilometers per second) and the broad emission line (FWHM ~ 820 kilometers per second) is $\Delta V \sim -250$ kilometers per second. The luminosity of the broad and narrow components is comparable (~ 10^{43} erg/second). The luminous [OIII] emission is the result of photoionization by the AGN, although it is less certain what is responsible for the production of the kinematically complex [OIII] emission.

To provide spatial information of the [OIII] emission, we constructed intensity, velocity, and full-width half-maximum (FWHM) maps of the [OIII]

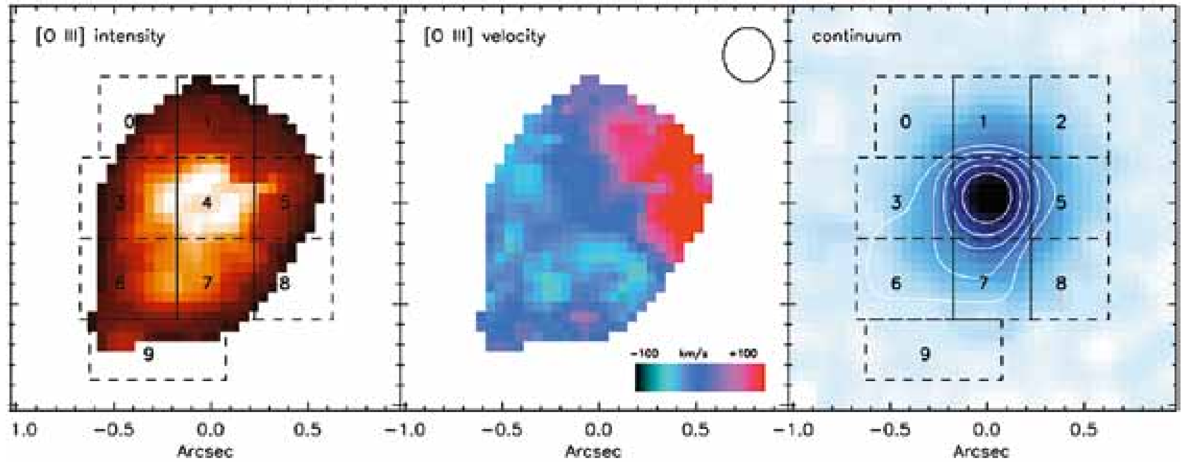

Figure 2. *[OIII] intensity (left), narrow [OIII] velocity map (middle), and line-free continuum image (right); circle at top right denotes the seeing disk size. The contours represent an intensity weighted map of the broad [OIII] emission components. The numbered regions of the broad [OIII] emission are plotted in Figure 3.*

emission from the IFU data cube. A χ^2 minimization procedure was used to fit each spectrum within the datacube, taking into account the greater noise at the positions of the sky lines. The spectra were averaged in increasingly larger spatial bins until a significant emission-line component was identified. To detect an emission line, we required a $> 5\sigma$ improvement over a simple continuum fit. To detect an additional broad component, we required a $> 4\sigma$ improvement over a single narrow emission-line fit. The basic [OIII] properties derived from the IFU datacube are shown in Figure 2.

Evidence for an Energetic Galaxy-wide Outflow

Narrow [OIII] emission is detected across an area of ~ 14 kiloparsecs. The emission is blue-shifted and red-shifted (with respect to the intrinsic redshift of the galaxy) to the southeast and northwest of the nucleus, respectively. The velocity field of this narrow [OIII] emission may be dominated by the host-galaxy rotation, although it is not clear that this is the only plausible explanation; see Figure 1.

Broad [OIII] emission is detected across ~ 4-8 kiloparsecs at the nucleus and to the southeast of the nucleus. The radial extent, velocity offset, and FWHM of the broad [OIII] emission is shown in Figure 2 (right) and Figure 3. The broadest [OIII] components clearly correspond to those with the largest velocity offset. The characteristics are similar to those found in some distant radio-loud AGN and are consistent with what would be expected for an energetic galaxy-wide outflow. Assuming that the broad [OIII] emission is due to an energy-conserving bubble expanding into a uniform region, the kinetic energy required to produce the broad [OIII] features is of order ~ $(0.6\text{-}5) \times 10^{44}$ ergs per second. Over a typical AGN/starburst lifetime of ~ 30 million years, the total injection of energy into the outflow would be of order ~ $(0.3\text{-}3) \times 10^{59}$ ergs, which is comparable to the estimated binding energy of the galaxy spheroid. This analysis is based on a simple model and should only be considered illustrative with uncertainties at the level of an order of magnitude. Given the limited constraints available for high-redshift systems, a more complex model is not yet warranted. However, it does indicate that the large-scale outflow in SMM J1237+6203 may be energetic enough to unbind at least a fraction of the gas from the host galaxy.

What is driving this large-scale energy outflow? Both AGN activity and star-formation processes provide plausible candidate explanations. Assuming that ~ 30 percent of the mass accreted onto the black hole is also liberated as an accretion-disk outflow (as motivated by observations of nearby AGN), the initial energy input into the accretion-disk wind would be of order ~ 10^{45} ergs per second. Therefore, so long as ~ 6-50 percent of this energy can be coupled to the host-galaxy gas, an accretion-disk wind in SMM J1237+6203 could drive the large-scale outflow. Similarly, assuming a typical star-formation rate for submillimeter-emitting galaxies of ~ 1,000 solar masses per year, the predicted energy injection from supernovae winds would be of order ~ 3×10^{44} ergs per second. If ~ 20-100 percent of this energy can be coupled to the host-galaxy gas, then star-formation activity could also drive the large-scale outflow. We cannot distinguish between these two

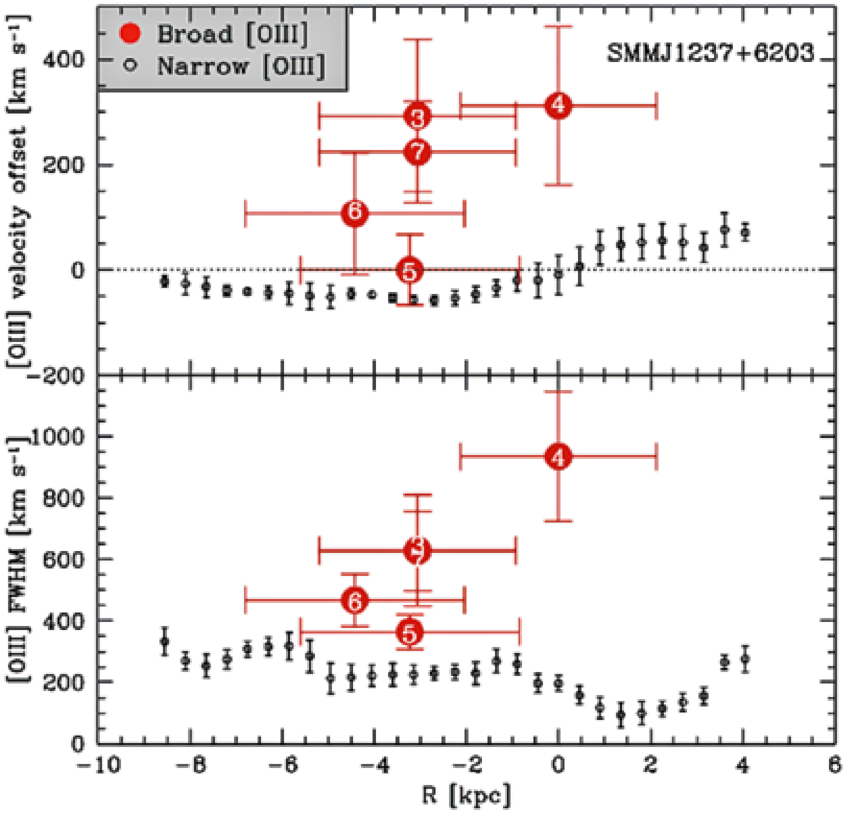

Figure 3. *Velocity and FWHM components of the broad and narrow [OIII] emission plotted as a function of radius from the nucleus. The numbered regions correspond to those indicated in Figure 2.*

different scenarios on the basis of the current data. However, given the comparatively modest radio luminosity from SMM J1237+6203, we can rule out the possibility that the outflow is driven by radio jets, in contrast to that found in distant radio-loud AGN; the gas coupling efficiency in SMM J1237+6203 would need to be unrealistically high (~ 10,000 percent), assuming typical radio-jet models.

Our work indicates that other processes in addition to radio jets are driving energetic outflows in the distant universe. It isn't clear whether the energetic galaxy-wide outflow that we have uncovered in SMM J1237+6203 is common in either radio-quiet AGN or ultra-luminous infrared galaxies. However, since both populations are orders of magnitude more common than radio-loud AGN at $z \sim 2$, if even just a fraction of either population hosts such galaxy-wide outflows, then their global contribution to the injection of energy into the host galaxy could be very significant and even dominant. The NIFS IFU observations for the remainder of our radio-quiet sample should provide at least a first-order step towards addressing this issue.

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by Ben Davies

A Massive Star is Born

One of the greatest mysteries in astronomy remains how the most massive stars are formed. Opinion is still sharply divided: Is the formation of massive stars a scaled-up version of low-mass star formation, or are completely different physical processes involved?

The mystery is due in part to the rapid formation timescales of such stars (10^5 years), which means that the star can have reached its final mass and be fully formed while it is still heavily obscured at visible wavelengths by its natal molecular cloud. If one wants to see into the heart of a stellar nursery and catch a massive star in the act of forming, one needs to use infrared observations where the obscuration due to dust is much lower.

Addressing this question of massive star formation is not straightforward. First, the technical requirements of such observations are challenging. Simple imaging is not enough; one needs to have spatially resolved spectroscopy of the inner nebula to probe the temperatures and dynamics of the gas surrounding the star. In addition, very high spatial resolutions are required ($<$ 0.5 arcsecond) in order to detect the inner 1,000 AU of objects at kiloparsec distances. Fortunately, the Gemini Near-infrared Integral Field Spectrometer (NIFS), backed-up by the Altair adaptive-optics system, fulfills these requirements.

Second, there is the problem of catching the star "in the act" of formation. As massive stars have comparatively short lifetimes (a few million years), and the formation phase is less than a tenth of this, the number of massive proto-stars in the Milky Way Galaxy is thought to be low. However, there is a well-known object which we can use as a testbed to study the formation of a massive star. The object, W33A, is a massive protostar with a luminosity approaching 10^5 times that of our Sun, and hence an inferred mass of at least $10M_\odot$ (see left-hand panel of Figure 1 for a wide-field image of W33A). Here, we present a NIFS+Altair

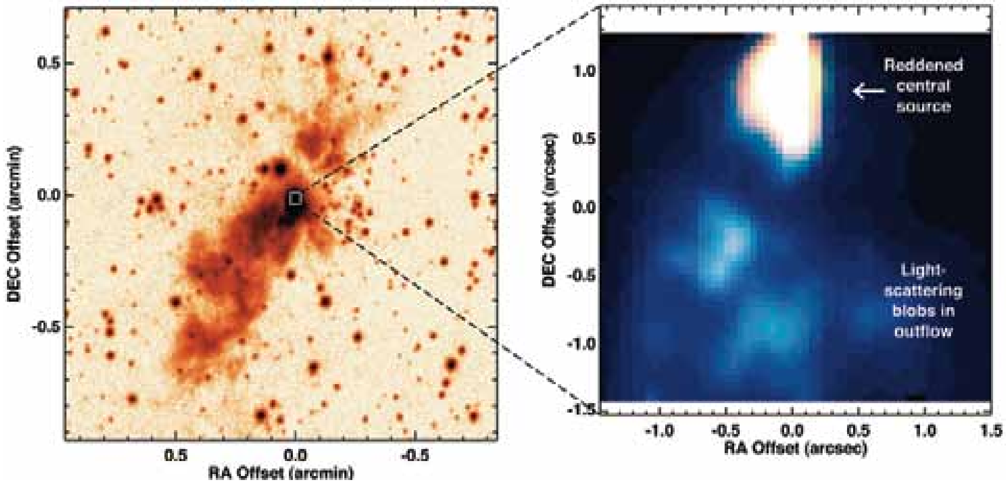

Figure 1. *Wide-field K-band image of W33A, taken from UKIDSS. Right: Near-infrared three-color image of the heart of W33A, made from the NIFS datacube with color channels at 2.083 µm (blue), 2.185 µm (green), and 2.273 µm (red). The major features of the image have been identified.*

study of W33A and its inner nebula, with the aim of shedding light on the processes which form the most massive stars.

Gemini NIFS+Altair Observations

Data were taken on the nights of April 16, and May 25, 2008. The observations had a spectral resolution of $\lambda / \lambda \sim 5300$ over the wavelength range 2.0-2.4 µm, across the full NIFS field-of-view of 3×3 arcseconds. We observed the target and neighboring sky in an ABBA pattern. The total integration time on-target was approximately 20 minutes. In addition to the science target, we took the standard set of NIFS calibration frames. The Altair adaptive-optics system helped us achieve a spatial resolution of ~ 0.1 arcsecond. Using the NIFS data analysis software, we generated a datacube of W33A: a high-resolution image of the star-forming region's core, with a spectrum at every pixel in the field-of-view.

In the left-hand panel of Figure 1, the wide-field image of W33A is shown as obtained in the UKIRT Infrared Deep Sky Survey (UKIDSS). The morphology suggests a bipolar flow, with the systemic orientation such that the southeastern lobe is approaching us. A three-color image of the heart of W33A is shown in the right-hand panel of Figure 1, made by taking three separate "slices" through the NIFS datacube. The central source can be seen at the top of the image, and appears orange due to it being heavily reddened. Meanwhile, the clumps to the south appear blue because the emission is predominantly due to scattered light from the central source.

The predominant spectral features that we observe are those of Brγ (ionized hydrogen), and both emission and absorption from molecular CO (Figure 2). The CO in emission indicates hot gas (~ 3,000 K), while the CO absorption must necessarily come from very cool gas (~ 30 K). These hybrid spectral features suggest that the two spectral features trace very different regions of the nebula.

Evidence for an Ionized Bipolar Jet

From the Brγ emission, we know that there is

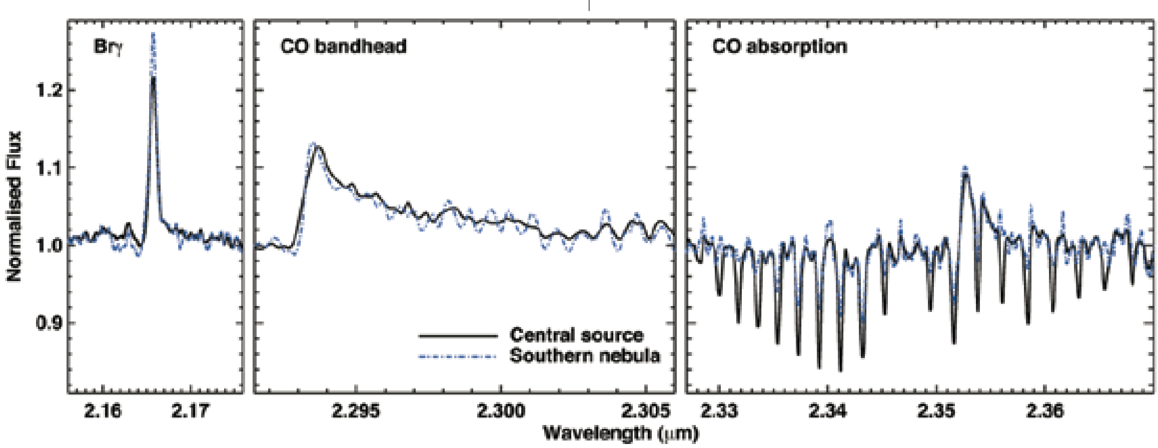

Figure 2. *Select spectral regions from the datacube, showing the main features present in W33A's spectrum. The spectrum of the central source is shown in black, while the spectrum as seen from the scattered light in the southern nebula is shown in blue.*

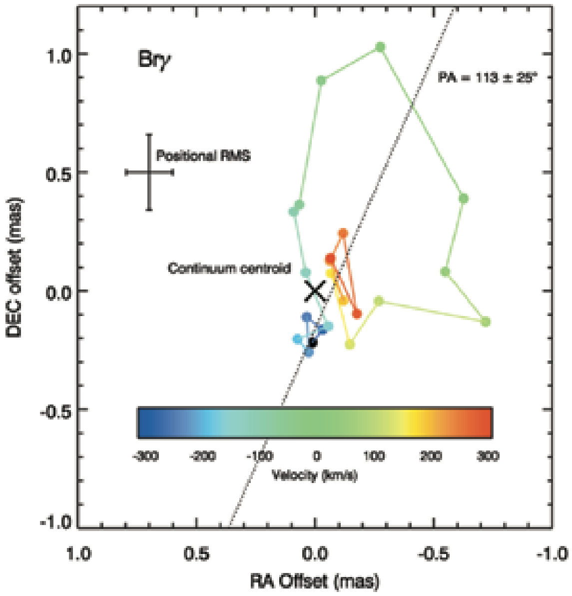

Figure 3.
Spectro-astrometric signature of the Brγ line. The high-velocity (›200 kilometers/second) emission is found to be located northwest and southeast of the centroid of the continuum emission, indicated by the cross. The position angle of this high-velocity feature is consistent with the large-scale outflow seen in Figure 1.

ionized gas within the W33A nebula. To trace the morphology of this gas, we use a technique known as *spectro-astrometry*. At each spectral channel in the datacube, we very precisely measure the location of the central source's flux peak. As we scan across the Brγ emission line, we chart the change in spatial position of this centroid relative to that of the neighboring continuum.

The results of this analysis are shown in Figure 3. We see that the high-velocity emission (|v| › 200 kilometers/second) appears to form an elongated structure, with the blue-shifted emission coming from the southeast and the red-shifted emission coming from the northwest. This suggests that the ionized gas is located in an outflowing bipolar jet, oriented such that the southeastern lobe is moving towards us. The ionized jet is therefore co-aligned with the larger scale outflow seen in the left-hand panel of Figure 1.

Evidence for a Rotating Molecular Torus and Circumstellar Disk

We now turn our attention to the CO absorption. By isolating these features in the datacube, we see that the morphology of the molecular absorption is very different from the continuum emission, and is located in an extended structure aligned roughly east-west (Figure 4, left panel). By measuring the velocity centroid of the CO absorption at each spatial pixel in the datacube, we made a velocity map of the molecular material, finding that it displays a velocity gradient along the long-axis of the extended structure – the classic signature of rotation. Our analysis of the CO absorption lines therefore suggests that the cool molecular material is located in a rotating "torus." Moreover, the position angle of this structure is aligned perpendicularly to both the large-scale outflow and the ionized bipolar jet of Figure 3. From the distance to W33A, the angular size of the torus, and the rotational profile, we calculate that the mass of the central object is $15^{+5}_{-3} M_{\odot}$.

In addition to the torus, we also see indirect evidence for a circumstellar disk. The presence of CO bandhead emission (center panel, Figure 2), which must come from material with a temperature of around 3000 K, is typically explained as arising in a flattened circumstellar structure around 1-3 AU from the central star. When we compare the bandhead profile as seen directly from the central source with that as reflected towards us by the southern nebula, we see that the "direct" emission shows evidence of being broadened (i.e. smoothed-out) with respect to the "reflected" profile from

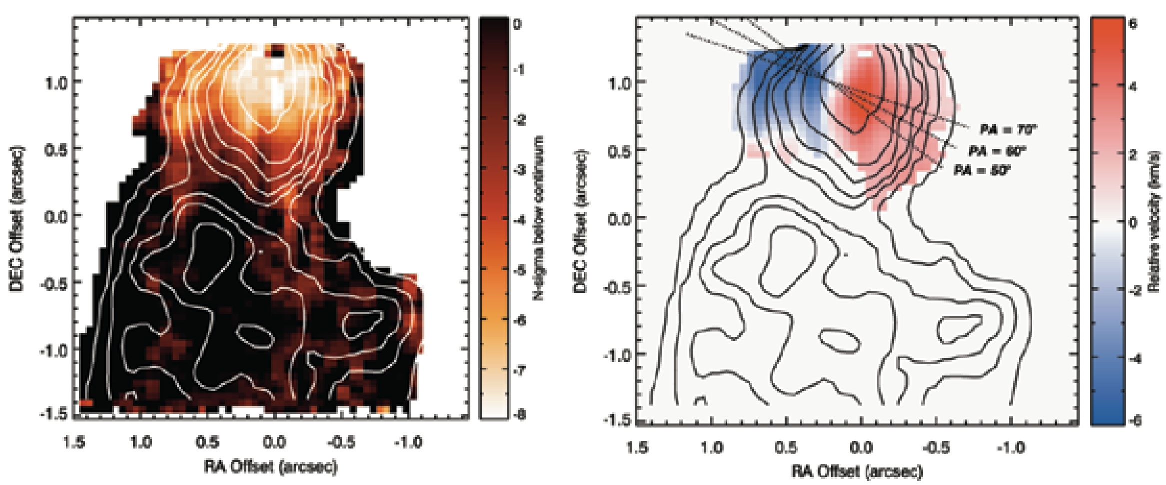

Figure 4.
The morphology and dynamics of the CO absorption region. The left panel shows that the absorption is located in a flattened, extended structure around the central source. The right panel shows the kinematics of this structure, showing the classic signature of rotation. The contours indicate the morphology of the continuum emission.

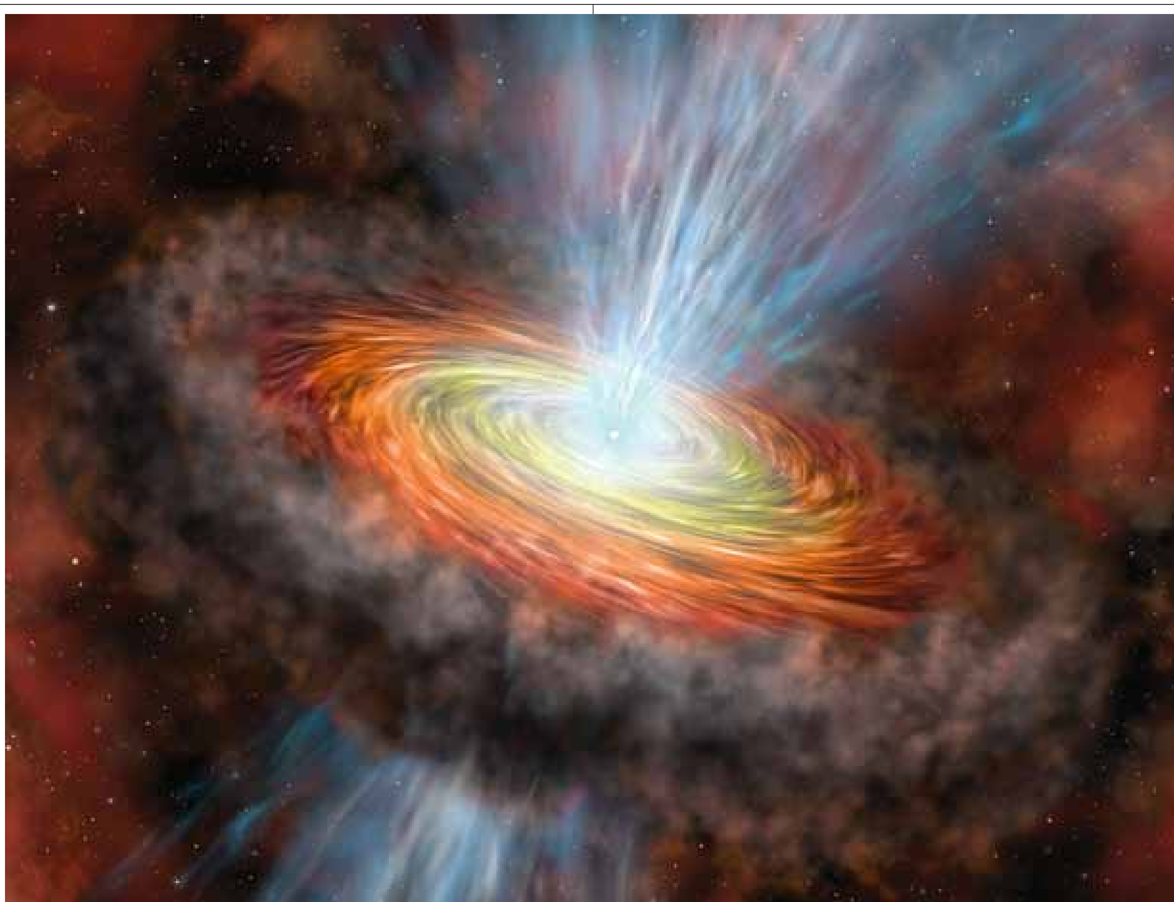

Figure 5. *Artist's impression of the W33A system, with its circumstellar disk, cool rotating torus, and ionized bipolar jet. (Gemini Observatory artwork by Lynette Cook)*

the southern nebula. The "direct" profile has a shallower blue edge, while the "reflected" profile has much more pronounced spikes in the region 2.295-2.305 μm (compare the blue and black lines in Figure 2). By assuming that this broadening is again due to rotation, we find that the circumstellar disk orbits a mass with a lower limit of 10^{+9}_{-5} $M_{\odot}$, and so is consistent with the mass central to the torus.

Taken together, our findings for the W33A system have a reassuringly familiar feel to them. The circumstellar disk, surrounded by a cool molecular torus, oriented perpendicularly to a fast bipolar jet, are all features commonly associated with the formation of stars with masses similar to our own Sun. However, in the case of W33A, we have been able to show that the mass of the star is at least 10 times as big as the Sun. Furthermore, the presence of a bipolar jet is the "smoking gun" that tells us accretion is ongoing, and that the star continues to grow. These results are the best evidence yet that the formation process of massive stars is similar to that which formed our own Sun some 4.6 billion years ago.

For more information, see:

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by Barry Rothberg

Underweight or Blinded by Youth:

Finding the True Mass of Galaxy Mergers

Galaxy mergers have been keeping astronomers busy for nearly a century puzzling over the forces that could cause these objects to appear so misshapen and twisted. Almost 40 years ago, Alar and Juri Toomre (Massachusetts Institute of Technology, University of Colorado, respectively) first suggested a gravitational waltz between two gas-rich spiral galaxies as a viable mechanism. As two galaxies pass close enough for their gravitational fields to exert influence on each other, tidal tails form, the pair become interlocked in an exquisite dance, and gas from each galaxy is funneled into the gravitational center of the interaction. The tango concludes with an enormous burst of star formation fueled by the gas and their coalescence into a new, more massive galaxy. The dance was not only commonplace, they argued, but the main mechanism by which all or most elliptical galaxies in the universe formed. The "Toomre Hypothesis" is now central to the current cosmological paradigm.

As systems merge, not only do the galaxies form new stars and grow larger but their dark-matter haloes grow as well. Thus, determining the mass of such systems can be a tricky proposition. One effective method is to observe the motions of the stars, or rather, the effect of the sum total of these stellar motions using spectroscopy. In elliptical galaxies, stars do not move in coherent circular orbits, but move in many different types of orbits – some circular, some elliptical, and perhaps (as some theoreticians speculate) exotic fish or pretzel-shaped orbits! Because some stars move towards us, while others move away (all by different amounts), the spectroscopic absorption lines appear both red and blue shifted, with all of these shifts superimposed on each other. The result is that absorption lines appear broadened (see Figure 1). This is called velocity dispersion (σ). The larger the σ, the larger the mass of the galaxy.

In elliptical galaxies, σs are normally measured at optical wavelengths, most often at ~ 0.5 μm (approximately the peak wavelength at which humans perceive light) using one of several magnesium absorption lines, but also measured at ~ 0.85 μm (slightly red of where humans perceive light) using a triplet of atomic calcium

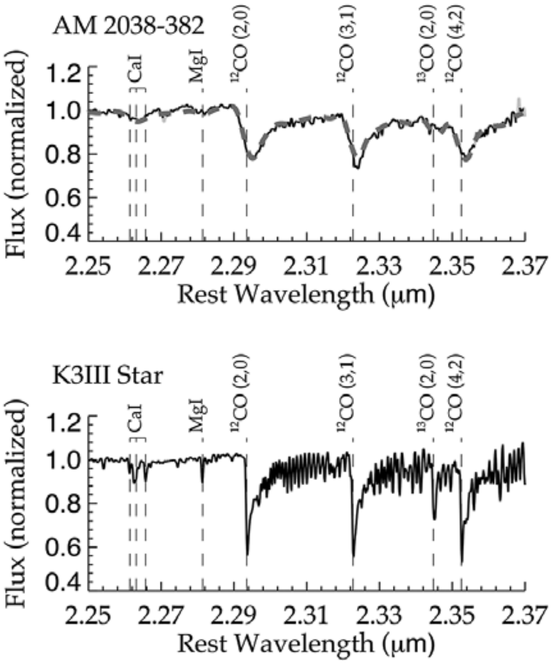

Figure 1. *Infrared spectra of the galaxy merger AM 2038-382 (top) and a K-type red giant star (bottom), both observed with Gemini Near-Infrared Spectrometer (GNIRS) on Gemini South. The dashed gray line overlaid on the merger in the top panel is the broadened stellar spectrum from the bottom panel. Also shown are the stellar absorption lines within that wavelength range.*

absorption lines. However, measuring the mass of star-forming galaxies using these optical absorption lines could be complicated by the presence of dust, which blocks much of the stellar light. Observations of stellar lines in the near-infrared, specifically carbon monoxide (CO) at 1.6 and 2.3 μm, were selected as an alternative for two reasons: 1) because longer wavelengths of light are less affected by the presence of dust; and 2) the CO molecule is present in the same type of stars used at optical wavelengths to measure σ.

The dustiest mergers are also the brightest at infrared wavelengths; dust particles absorb photons of ultraviolet light, heating the dust and then reradiating it away as infrared photons. Many such galaxies were discovered by the Infrared Astronomical Satellite (IRAS), which conducted an all-sky survey at infrared wavelengths of 12, 25, 60, and 100 μm. Galaxies 100-1,000 times more luminous than the Milky Way at these wavelengths were classified as Luminous and Ultraluminous Infrared Galaxies (LIRGs and ULIRGs). Subsequent observations showed that they contained vast quantities of cold hydrogen gas and were adding mass equivalent to 1,000 Suns every year.

Therefore, it came as quite a surprise when σs measured from observations of the CO molecule showed LIRGs and ULIRGs to have significantly less mass than a typical elliptical galaxy. Even though LIRG and ULIRG mergers appeared to be forming more stars than any other type of galaxy, once they exhausted their fuel, all that would remain would be an elliptical galaxy less massive than our own Milky Way!

However, observations using the calcium triplet (CaT) absorption lines showed remarkably different results. Two published results, one by Barry Rothberg & Robert Joseph (University of Hawai'i) found that merging galaxies (including both non-LIRG and LIRG mergers) had masses equivalent to, and often much greater than, typical elliptical galaxies. Surprisingly, CaT and CO σs of the same LIRG mergers yielded different masses. Even more surprising, the σs measured with the near-infrared CO molecule were systematically smaller than the σs measured with the optical CaT absorption lines.

These results are absolutely counter-intuitive to what astronomers expect. Dust should block light, and in galaxies with significant amounts of dust, we expect the light needed for measuring the true mass of the galaxy will be hidden from view. Near-infrared light can pierce more dust because of its longer wavelengths, thereby allowing astronomers to collect more light closer to the heart of the galaxy. Stunningly, it appeared as if the opposite effect was occurring. This left us pondering whether there was some peculiarity in either the atomic CaT or molecular CO lines that affected σ; such an alarming assessment implied the mass estimates in all galaxies

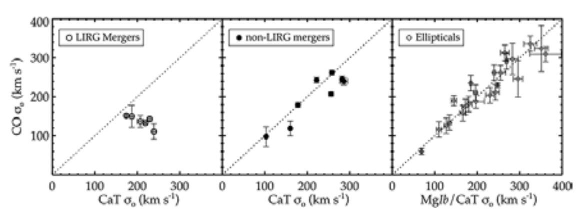

Figure 2. *For luminous infrared galaxy (LIRG) mergers (left), central velocity dispersion measured with CO (CO σ_o) is significantly lower than that measured with the Calcium II Triplet (CaT σ_o). For non-LIRG mergers and normal elliptical galaxies (middle and right), there is no meaningful difference between the two techniques.*

could be suspect! Or perhaps this discrepancy was limited to only IR luminous systems. To complicate things further, the only mergers for which optical and near-infrared σs had been measured were IR luminous systems.

Solving this conundrum required a comparison of σs measured from optical and near-IR stellar lines in galaxies other than IR-bright mergers. For this work, the author and Jacqueline Fischer (Naval Research Laboratory), selected both elliptical galaxies

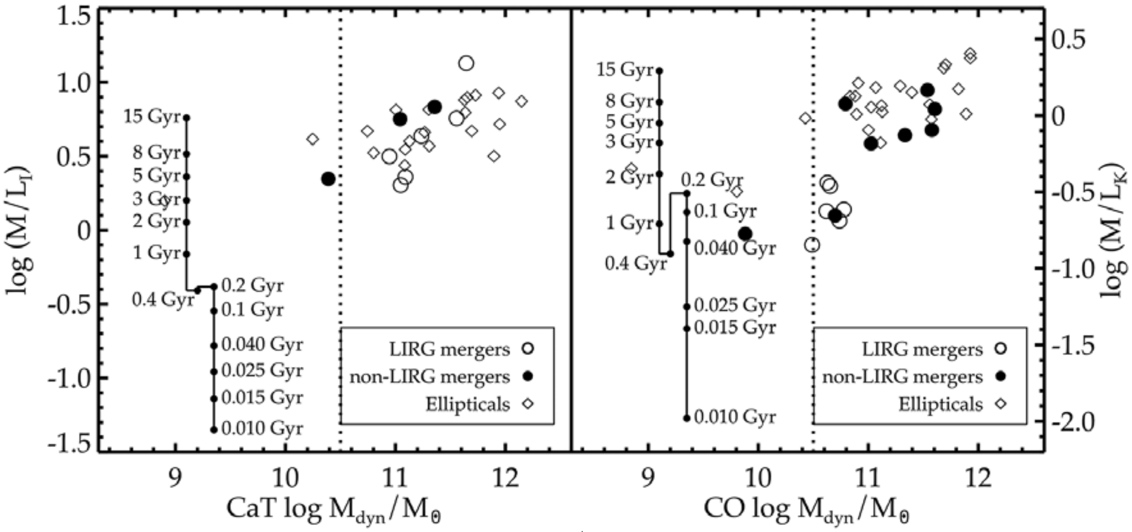

Figure 3. *Optical (left) and near-infrared (right) comparison between mass (M) and mass-to-light ratio (M/L). The vector shows the evolution of M/L over time for stellar populations. LIRGs (open circles) appear to be younger and less massive in the near-IR (right) than in the optical (left), while non-LIRGs and ellipticals appear the same at both wavelegnths.*

and non-IR bright mergers as control samples. Our hypothesis was that the star-forming properties of LIRGs and ULIRGs were responsible for this "σ-Discrepancy." Using GNIRS on Gemini South, we observed the CO molecular absorption bands to measure σs in six non-LIRG mergers and one elliptical galaxy. These were compared to earlier work with Robert Joseph which measured σs from the CaT absorption lines in the same galaxies. To improve statistics, we added additional elliptical galaxies from recently published papers and compared these with the LIRG and non-LIRG mergers (see Figure 2).

Figure 2 did allay our first fears that either or both the CaT or CO stellar lines could furnish false masses in all galaxies. Instead, we found that the degree of disparity between optical and near-infrared σs was strongly correlated with their IR luminosities. A further comparison of characteristics revealed that this σ-Discrepancy strongly correlated with the amount of dust and 20-cm radio emission (often a sign of star formation). The control-sample of elliptical galaxies showed no statistical correlation among the same parameters.

The σ-Discrepancy is caused by the presence of discrete stellar populations seen at different wavelengths. Figure 3 compares mass-to-light ratios (M/L) with mass in the optical (left) and near-infrared. Overplotted is a model showing the evolution of M/L of a stellar population developed by Claudia Maraston (University of Portsmouth). It impresses upon us that Red Supergiants (RSGs) and Asymptotic Giant Branch (AGB) stars in the near-infrared begin to appear in stellar populations after a few million and a few hundred million years, respectively. They are both the end-stages of stars significantly more massive than our Sun. When these stars appear, not only do they add considerable luminosity to a galaxy, but they have very strong CO absorption at 1.6 and 2.3 μm, the same CO used to measure σ.

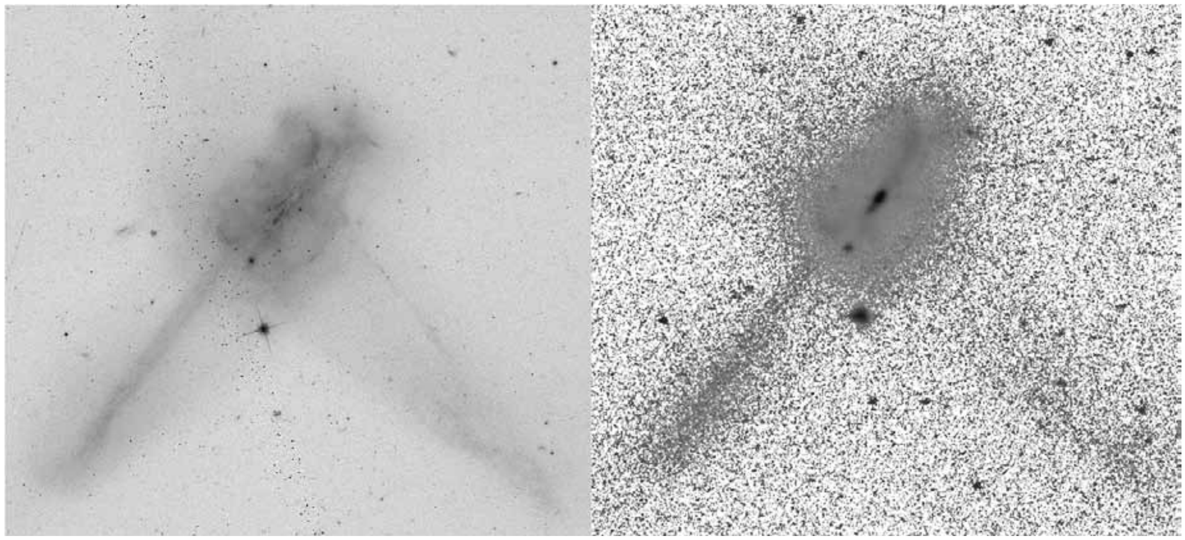

Figure 4. *I-band image obtained with the Advanced Camera for Surveys on the Hubble Space Telescope (left) and K-band image obtained with the QUIRC imager on the University of Hawai'i 88 inch telescope (right) of the LIRG merger Arp 193. The two images are the same field-of-view. Note the dust obscuration (left) of the central (disky) luminous source seen in the K-band image (right).*

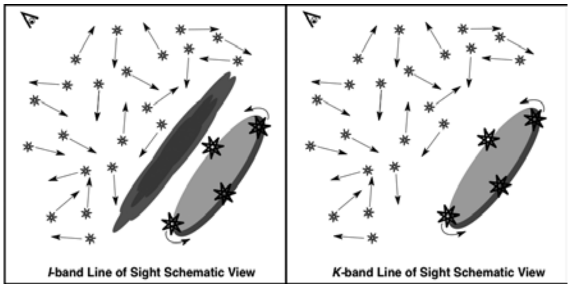

Figure 5. *Schematic views illustrating the differing effects of dust on the light from a rotating disk of luminous young stars in the I-band (left) and K-band (right). The observer's line-of-sight is denoted by the eye in the upper left corner. The central disk of rotating RSG or AGB stars is pictured in both panels, the dark gray clouds represent the stronger effects of dust at optical wavelengths (left panel), and the smaller sized stars represent late-type giant stars moving in random orbits (both panels). At optical wavelengths the dust acts like a coronagraph, masking out the rotating disk of young stars.*

Figure 3 also reveals that LIRGs appear very different at optical and near-infrared wavelengths. At optical wavelengths, they are old, massive, and statistically indistinguishable from elliptical galaxies. In the near-infrared, LIRGs appear younger and with less mass. While future studies will allow us to precisely pinpoint the ages of the stellar populations, Figure 3 clearly shows that in the near-infrared, the ages of the stellar population match the time at which RSGs or AGB stars appear.

This leads us to conclude that both the light and the CO molecules observed in LIRGs comes predominantly from these young stars which formed after the merger began. However, at optical wavelengths, the presence of dust blocks these young stars from view. The light in the I-band images and CaT absorption lines we use to measure the properties of mergers come from much older stars that were part of the progenitor gas-rich spirals. Where once these stars enjoyed simple circular orbits in their spiral hosts, the tempestuous merging event changed their orbits. Their new orbits reflect not only the combined mass of their new host, but the presence of new stars germinating in the core of the new proto-elliptical galaxy. The difference in the central regions can also be seen in Figure 4.

What are we really probing with the observations of the CO absorption feature? As the gas from progenitor spiral galaxies is funneled into the gravitational center of the merging system, it retains some angular momentum, forming a rotating gas disk. Such gas disks have been observed at millimeter and sub-millimeter wavelengths. The gas in this disk furiously forms stars, producing copious quantities of dust, possibly providing fuel to a central black hole, and ultimately leading to the formation of a massive central black hole.

Our K-band images indicate that the IR luminous mergers exhibit disk shaped lines of flux, or isophotes, on the same spatial scales we measure σ from CO. This tells us that a significant portion of the stars reside in a disk, rather than move in random orbits. The presence of a disk affects σ because coherent (in this case circular) motion actually reduces the amount of random motion observed. Figure 5 provides a schematic representation of what we hypothesize is occurring. Young stars form in the rotating disk; the presence of dust shields this disk at optical wavelengths.

In the near-infrared, light from the disk penetrates the dust and dominates what astronomers see. Observations of σ are almost meaningless in the near-infrared because they do not reflect the total mass of the galaxy, nor can they be used to measure the mass of the disk or even the central black hole. In fact, recent work has shown that near-IR σs used to measure the mass of central black holes in ULIRGs yield systematically smaller masses than other methods.

The next step in our work is to directly observe the stellar disks in IR luminous mergers using three-dimensional spectroscopy via Gemini's Near-Infrared Integral Field Spectrometer (NIFS) in conjunction with laser guidestar adaptive optics (AO). Each pixel is a spectrum, and from this one can make two-dimensional maps of stellar motion and stellar age. This will allow us to measure the size, rotation, luminosity, mass, and age of the disk. NIFS+AO will also afford us the opportunity to probe the connection between such disks and the formation of super-massive black holes which power Active Galactic Nuclei. The fun is only just beginning!

For more information, see:

Rothberg, B., & Fischer, J., 2010, *ApJ*, **712**, 318

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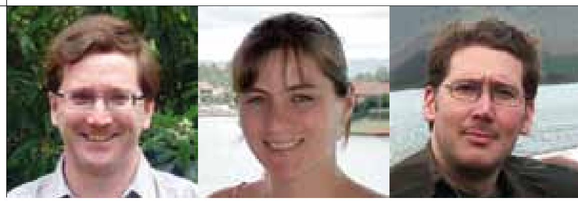

by Stuart Ryder, Catherine Farage
& Rob Sharp

The Nuclear Starburst Ring in IC 4933

High-spatial-resolution imagery of barred spiral galaxies occasionally reveals tightly wound rings within the central kiloparsec. Numerical simulations suggest that such circumnuclear rings may occur when the bar pattern speed is in some particular resonance with the natural epicyclic frequency with which a perturbed gas cloud will oscillate about its mean orbital radius. This leads to an increase in cloud collisions, and thus an elevated star-formation rate around the ring. The bar also seems to play a role in drip-feeding gas into these rings, which makes them fascinating laboratories for studying star formation in action. More than 100 nuclear rings are now known, but finding them and measuring their star-forming properties is still painstaking work. By using a wide-range of facilities, including Gemini, we found a nuclear ring with remarkably organized star formation in the otherwise innocuous barred spiral galaxy IC 4933. Our diverse data included a combination of wide-field, near-infrared (NIR) imaging from the 3.9-meter Anglo-Australian Telescope (AAT), NIR spectroscopy with the

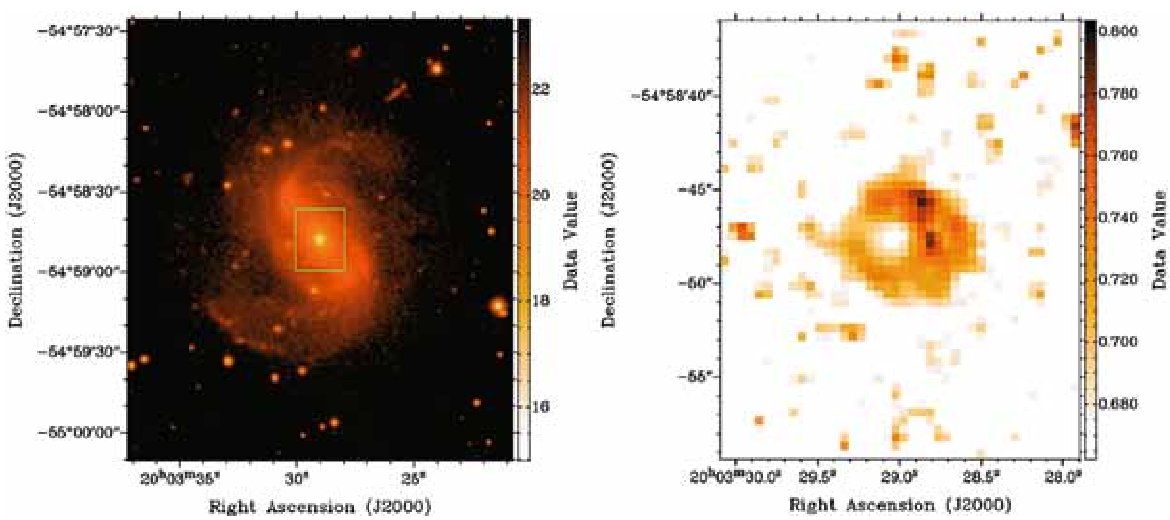

Figure 1.
A J-band image of IC 4933 from IRIS 2 on the AAT, with surface brightness in mag/arcsec² indicated by the vertical scale. A (J – H) color index map of the inset region marked in green is shown at right, with the color range indicated.

now-defunct Integral Field Unit (IFU) of the Gemini Near-Infrared Spectrometer (GNIRS) on Gemini South, (note, when it was decided to repair and move GNIRS to Gemini North, the IFU was not included, since this capability was better provided by the Near-infrared Integral Field Spectrometer, NIFS), and even poor-weather-queue optical imaging with the Gemini Multi-Object Spectrograph on Gemini South (GMOS-South).

Motivated by the realization that spiral galaxies which exhibit a stellar ring encircling their bar often harbor a nuclear ring as well, we embarked in 2003 on an imaging survey of galaxies in Ron Buta's *Catalog of Southern Ringed Galaxies* using the Infrared Imager and Spectrograph 2 (IRIS 2) instrument on the AAT. Nuclear rings stand out better in the NIR due to the reduced extinction compared with optical wavelengths, coupled with the rapid appearance of red supergiants within the first 10 million years (Myrs) or so of a burst of star formation.

AAO student intern Catherine Farage was tasked with making color-index images from the difference of the aligned J, H, and K images. Among the first 30 galaxies imaged, only one – the SBbc galaxy IC 4933 some 65 Megaparsecs distant – showed any hint of a nuclear ring, and then only in the color-index maps (Figure 1). The ring in IC 4933 is 5 arcseconds (1.5 kiloparsecs) in diameter, and noticeably redder than the background stellar population. In order to rule out the possibility that this ring feature is merely a silhouette due to dust, we requested a GMOS-South u' image in the poor-weather queue, which clearly shows dust lanes winding their way along the leading edge of the bar towards the nucleus, but no dust ring aligned with the NIR ring.

In principle, the NIR colors of a star-forming region can be used to directly infer its age. Figure 2 shows evolutionary tracks in the (J – H, H – K) diagram for two scenarios from the Starburst99 library (http://www.stsci.edu/science/starburst99/): an instantaneous burst (IB) with no subsequent star formation; and a constant rate of ongoing star formation (CSF), ending after 250 Myrs at the open square and triangle, respectively. The mean colors at the four cardinal points around the ring, as well as the background stellar population (open circle), are

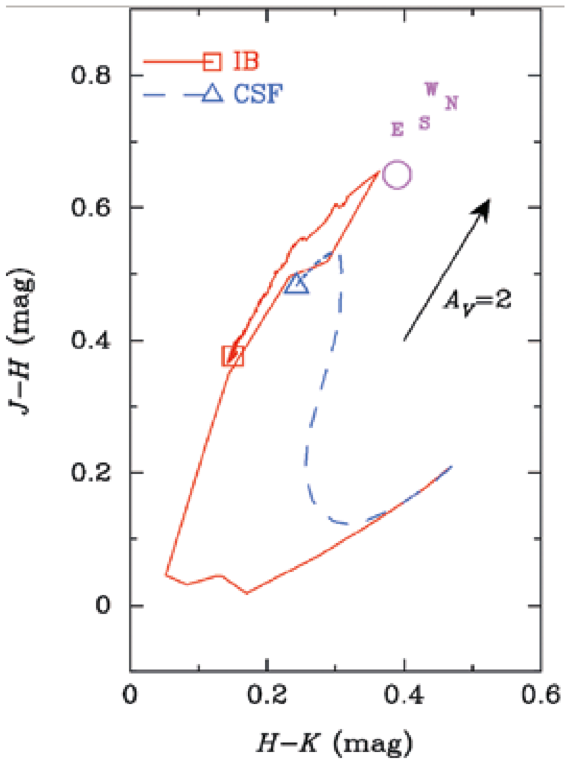

Figure 2. *This diagram shows the evolution with time of a star-forming region's NIR colors from Starburst99 models, for both an instantaneous burst (IB), and continuous star formation (CSF), compared to the NIR colors around the nuclear ring and in the bulge of IC 4933.*

marked in magenta, while the arrow shows the effect of reddening in each color by an amount of dust equivalent to 2 magnitudes of extinction in the optical V-band. Perversely, the effect of dust reddening almost exactly parallels the effects of aging, so that the observed colors around the ring can equally well be explained by either an instantaneous burst 5 Myrs ago with up to 6 magnitudes of visual extinction, or by continuous star formation for between 10 and 100 Myrs with only 2 magnitudes of extinction! In order to disentangle the effects of dust, aging, and duration of star formation, we need a better diagnostic which is somehow immune to reddening.

The Paschen-beta (Paβ) emission line of ionized hydrogen at 1.28 μm is an excellent tracer of newly formed massive stars, whose ultraviolet photons are readily absorbed by the surrounding gas and re-emitted in such lines. The equivalent width of Paβ is defined as the flux within the line, relative to the strength of the adjacent continuum near 1.28 μm. Since much of this continuum is produced by massive stars which formed 10 Myrs or so earlier, the equivalent width from a short-lived burst 10 Myrs ago will be much smaller than in the case of continuous star formation over the course of 10 Myrs, as shown by the Starburst99 models in Figure

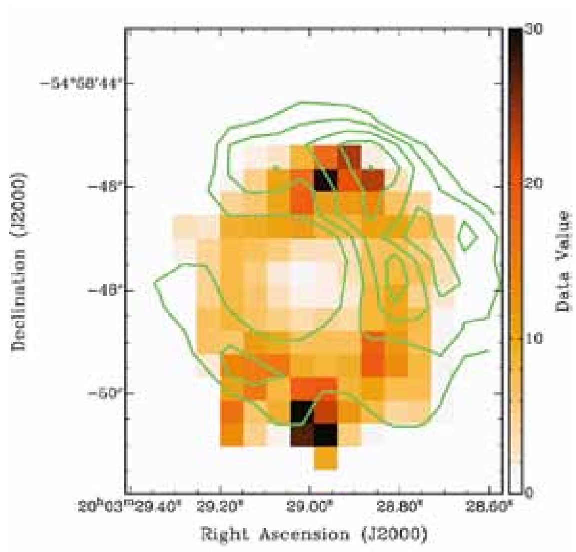

Figure 3. *The (J − H) color-index map from Figure 1 is shown here as contours overlaid upon the equivalent width of Paβ emission, in units of Angstroms marked at right.*

4. Assuming the gas, stars, and dust are well-mixed, the Paβ line and its continuum will suffer equal amounts of extinction, making the equivalent width much better suited for age-dating star formation than NIR colors.

We used the IFU of GNIRS to map the distribution of Paβ around the nuclear ring in IC 4933, and the comparison with NIR color is shown in Figure 3. In stark contrast to the color-index map, the Paβ equivalent width shows a clear bifold symmetry, reaching a maximum ~ 15 Ångstroms due north and south, more than twice the minimum observed to the east and west. The observed ranges are plotted in Figure 4, along with the predictions for Paβ equivalent width from the same Starburst99 models featured in Figure 2.

We conclude on the basis of this plot that the instantaneous burst scenario is far more likely, as it takes more than a billion years for continuous star formation to reach the observed levels. The star clusters in the north and south of the ring formed 6.6 Myrs ago, while those to the east and west are 0.3 Myr older. Having pinned down these ages, we can now use Figure 2 to derive separately the extinction around the ring, which ranges from 2 magnitudes in V in the east, up to 3.5 magnitudes in the north, consistent with the increase in reddening going counter-clockwise from the east.

IC 4933 has thus jumped from obscurity, to membership of a select group of galaxies that includes M100 and M83, whose nuclear rings show evidence of azimuthal age gradients. What circumstances might give rise to such well-organized star-formation patterns as this? Our current theories, backed up by numerical simulations, suggest that dust lanes along the bar axis correspond to shock fronts which result in gas clouds losing angular momentum, and effectively being channeled inwards along these dust lanes toward the ring. Gas is injected onto the ring at one of two opposing "contact points," much as passenger baggage at large international terminals is often deposited onto the carousel from two conveyor belts at either end simultaneously. These contact points are carried around at the pattern speed of the bar, somewhat slower than the orbital velocity in the ring, causing the clusters to drift away from their birth site (just as the carousel carries bags away from the conveyor belt outlet). After half an orbit of the ring, the oldest clusters become buried among newly formed clusters from the other contact point

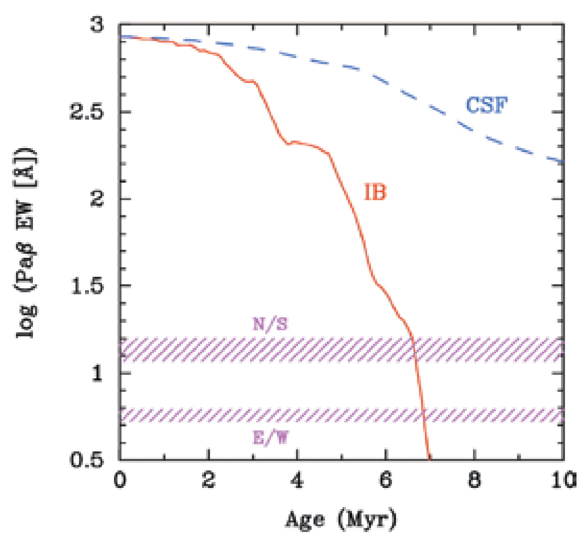

Figure 4. *The Paβ equivalent width observed in the North/South, and East/West quadrants of the nuclear ring of IC 4933, compared with model predictions from Starburst99.*

(not unlike the baggage carousel situation!), and the mean age becomes much younger.

The question that remains then is why don't all nuclear rings show such clear age sequences? The most likely explanation is that gas inflow along the bar and injection onto the ring is not continuous in time, but episodic or irregular. Disruption of the gas supply will terminate star formation, and after several orbits the aging clusters will be disrupted to the point where any age pattern will be smoothed out. We may simply have caught IC 4933 at an opportune time, but it took the combined power of three instruments on two telescopes to unravel the true nature of star formation buried deep within its core.

This work has benefited greatly from the assistance of another AAO student intern, Sam Illingworth from the University of Leicester. For further details, see our paper in the *Publications of the Astronomical Society of Australia*, **27**, 56 (2010), and is also available at http://arxiv.org/abs/0909.1371.

For more information, see:

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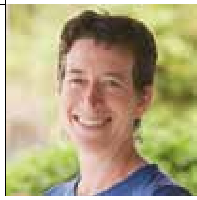

by Nancy Levenson

Recent Science Highlights

A Young Planetary-mass Companion to a Brown Dwarf

Hundreds of planetary-mass bodies have been detected outside the Solar System, but the characteristics of those planetary systems are sensitive to the search techniques employed. Radial-velocity measurements, which rely on the signature gravitational pull of the orbiting planet on the central star, have identified most of the known extrasolar planets, but this method is most sensitive to massive planets near the central source. In contrast, direct imaging is most sensitive to widely-separated bodies.

Kamen Todorov (Pennsylvania State University) and collaborators are using this latter method to find planetary-mass companions in the Taurus star-forming region. One particularly interesting example they have identified is a 5 - 10 $M_{Jupiter}$ companion to a brown dwarf. The objects are separated by 0.105 arcsecond, which corresponds to about 15 AU. Images from the Hubble Space Telescope and Gemini (using NIRI with the Altair adaptive optics system, see Figure 1) easily resolve the primary and its companion, and the multiple observations confirm the common proper motion of the pair.

The entire star-forming complex is young, with an age of less than about one million years, so the discovery supplies useful constraints on the formation process of this system. Three general scenarios for the formation of planetary-mass companions are: 1) dust in a circumstellar disk slowly agglomerates to form a rocky planet about 10 times larger than the Earth, which then accumulates a large gaseous envelope; 2) instability in the disk causes a clump of gas to quickly collapse and form an object the size of a gas-giant planet; or 3) rather than forming in a disk, a companion forms from the collapse of the vast cloud of gas and dust in the same manner, and at the same time, as the primary body. Only the last of these scenarios proceeds rapidly, and is

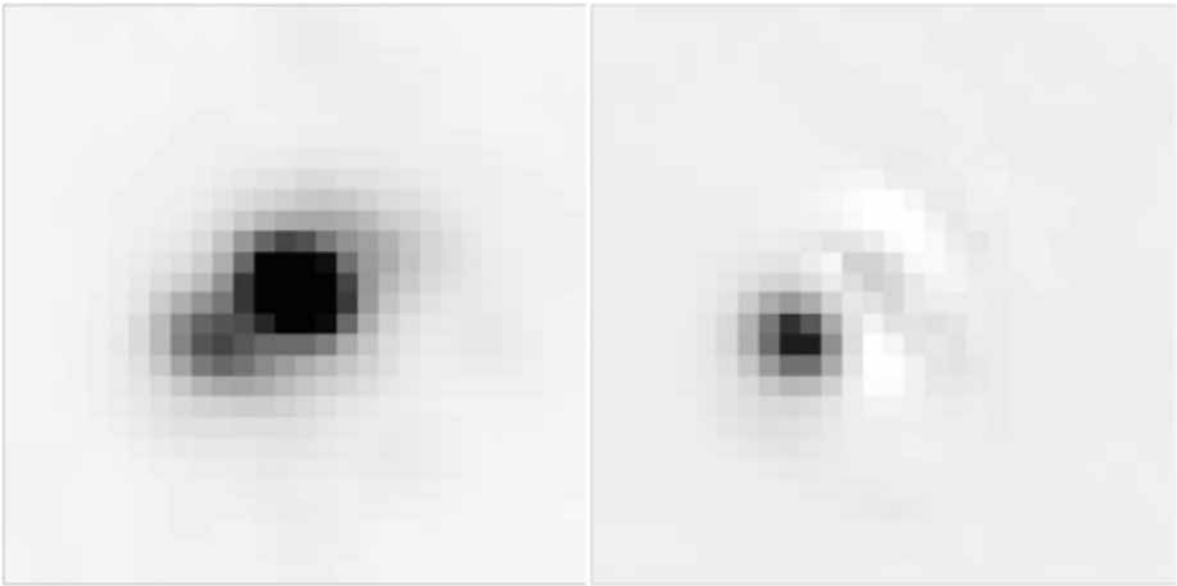

Figure 1.
(left) The NIRI/Altair near-infrared (K'-band) image of the young brown dwarf 2MJ044144 shows its planetary-mass companion offset to the lower left. (right) The brighter emission of the brown dwarf is subtracted, to show the companion more clearly.

therefore the most likely origin of this system. This is the same process by which stars form, so this work shows that the same method can extend down to planetary mass bodies.

The Gemini images also show a second pair of nearby objects. While the relationship among them is not confirmed, it suggests a quadruple system in which all four objects formed together. Such multiple formation is common among stars, further supporting the origin of planetary-mass bodies in the fragmentation of a large cloud. The complete results are published in *The Astrophysical Journal Letters* (K. Todorov, K. L. Luhman, and K. K. McLeod 2010, 713, L84).

Minor Mergers Help Grow Galaxies "Inside-out"

Looking into the distant universe, astronomers look into the past. Observations of distant galaxies directly reveal themselves as they once were. Indirectly they also indicate the stages of development that lead to the nearby galaxies like our own Milky Way as well as older galaxies in our current epoch.

Rodrigo Carrasco (Gemini Observatory) and collaborators used the Near-Infrared Imager and Spectrometer (NIRI) with the adaptive optics system Altair and laser guide stars on the Gemini North telescope to investigate galaxies at redshifts from $z = 1$-2 (when the universe was only 25 to 40 percent of its current age). These instruments afford high-angular resolution, which is essential when measuring fine spatial scales in distant galaxies. In these observations, the massive galaxies tend to be extremely compact, with sizes less than about two kiloparsecs, despite their large mass (stellar mass, $M > 10^{11} M_{Sun}$).

These deep images are sufficiently sensitive to allow determination of the properties of individual galaxies. In contrast, previous studies combined observations of different galaxies to improve sensitivity, providing average measurements of the galaxy samples. An important result of this current work is that the galaxies grow "inside-out" in a sense, adding mass to the outer regions beyond an initial dense core. Evolution over time will add stellar mass to the outer regions, resulting in galaxies more similar to those observed at the current epoch.

Moreover, the sensitive images show evidence for minor mergers in many cases, in which the galaxies consume some of their lower-mass companions (Figure 2). This merging process thus accounts for some of the growth in both size and mass to produce the normal galaxies of the local universe. Minor mergers would occur more frequently than major mergers (of galaxies of comparable mass), so the minor mergers are significant in the growth and evolution of galaxies. The full results will be published in the *Monthly Notices of the Royal Astronomical Society* (E. R. Carrasco, C. J. Conselice, and I. Trujillo, 2010).

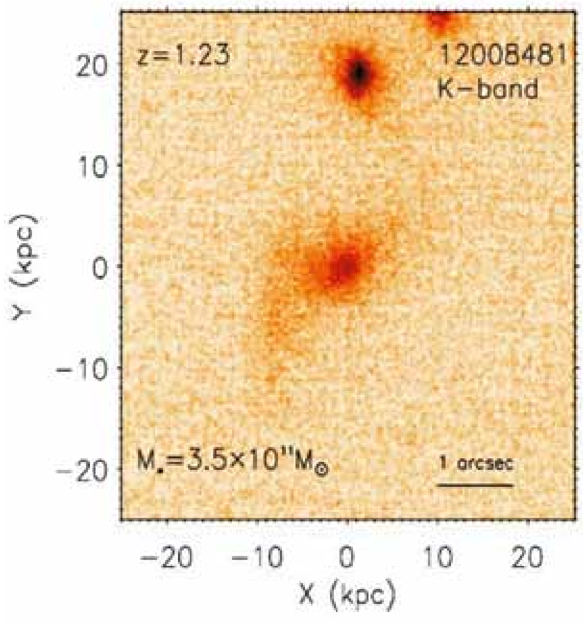

Figure 2. *The NIRI/Altair near-infrared (K-band) image of galaxy 12008481 shows that the stellar mass is physically compact, while the substructure within the image is evidence of past minor mergers.*

Dust and Ionized Gas in the AGN of Markarian 1066

The central engines of active galactic nuclei (AGN) are supermassive black holes that accrete material and their immediate surroundings reveal their effects. However, multiple physical processes can arise in the central regions of galaxies, and the presence of star formation and shocks, for example, can complicate the interpretation of observations. Rogemar Riffel (Universidade Federal de Santa Maria, Brazil) and collaborators have taken advantage of the simultaneous spatial and spectral measurements that NIFS and the adaptive optics system Altair afford to disentangle the physical processes of the central kiloparsec of the active galaxy Markarian 1066 (Mrk 1066). The accretion process produces hard continuum emission, which excites and ionizes the nearby gas. Line emission from ionized species is evident in a bicone that is aligned with a radio jet (Figure 3).

Dust hides the central engine of Mrk 1066 from direct view, but the dust absorbs and reprocesses the incident radiation to re-radiate at longer wavelengths. The NIFS observations show the dust in emission at infrared wavelengths, at a temperature of around 830 K. The smallest-scale emission is unresolved. This sets a maximum size of 35 parsecs for the dusty torus of unified AGN models, which account for a variety of observational differences among AGN in terms of viewing geometry, but not intrinsic differences.

Outflow is also a common consequence of accretion. In this case, radio emission traces the flow away from the central engine. The strongest near-infrared line flux is correlated with the radio emission, suggesting that the radio jet is partly responsible for the line flux (in addition to the primary continuum).

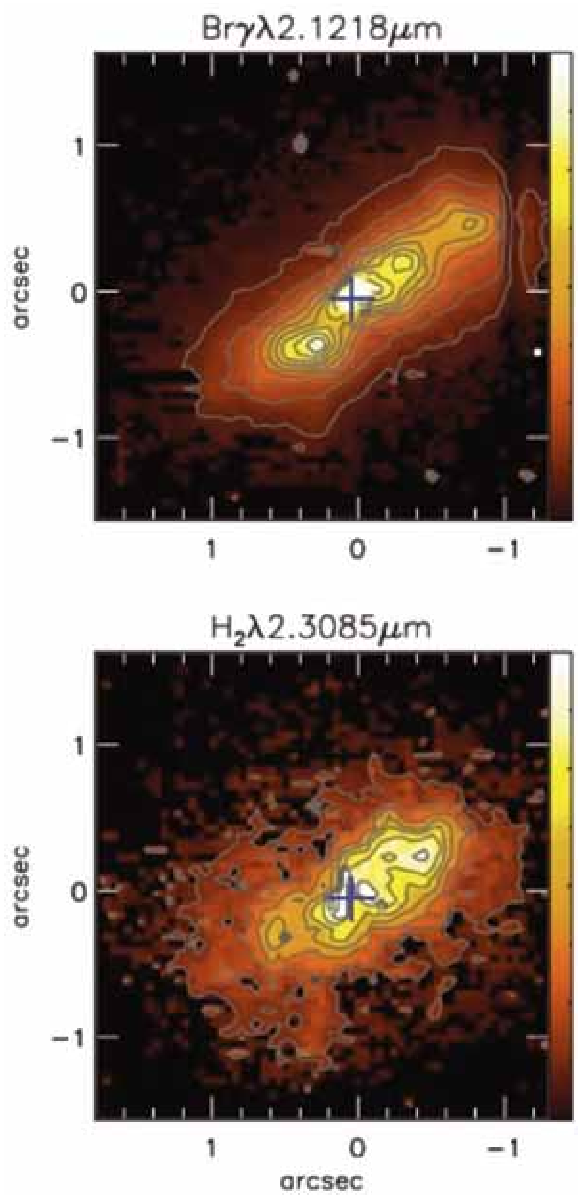

Figure 3. *The NIFS/Altair observations provide simultaneous spatial and spectral resolution of the center of the active galaxy Mrk 1066. Here the data show the emission from ionized hydrogen (top) and molecular hydrogen (bottom), with the brightest regions in white. The ionized emission is strongly concentrated along the central axis, while some diffuse radiation also excites the molecules.*

Ratios of emission-line fluxes are characteristic of particular excitation sources. Although Mrk 1066 certainly contains a powerful AGN, some of the central region of this galaxy shows the signature of star formation instead. Moreover, low-ionization states are measured perpendicular to the jet and ionization axis, suggesting that some diffuse radiation leaks out of the main ionization cone.

Complete results appear in *Monthly Notices of the Royal Astronomical Society* (R. A. Riffel, T. Storchi-Bergmann, and N. M. Nagar, 2010, 404, 166).

Tracing Star Formation with Globular Clusters

One way to begin to answer the questions of when and how stars formed in galaxies is to measure their globular clusters. The advantage of globular clusters is that their stellar populations reflect what is essentially a single formation-time with uniform conditions, particularly concerning the abundance of metals. Moreover, globular clusters tend to be relatively free of dust, so their optical light emerges freely.

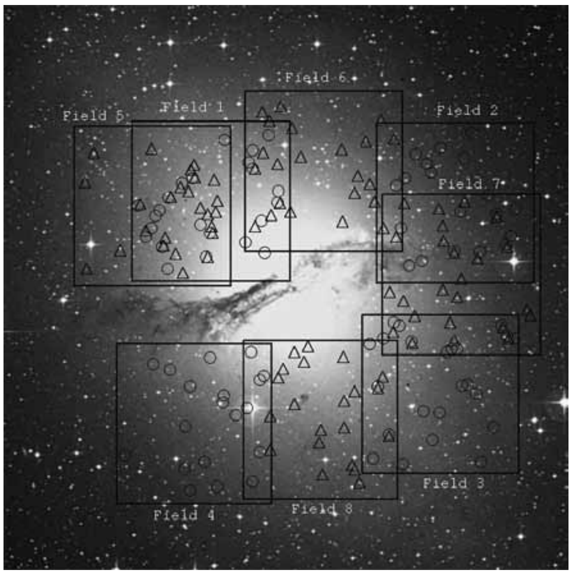

Figure 4. *Digital Sky Survey image of NGC 5128, with GMOS fields (squares) superposed. Globular clusters are marked with circles and triangles, observed in 2005 or 2007, respectively.*

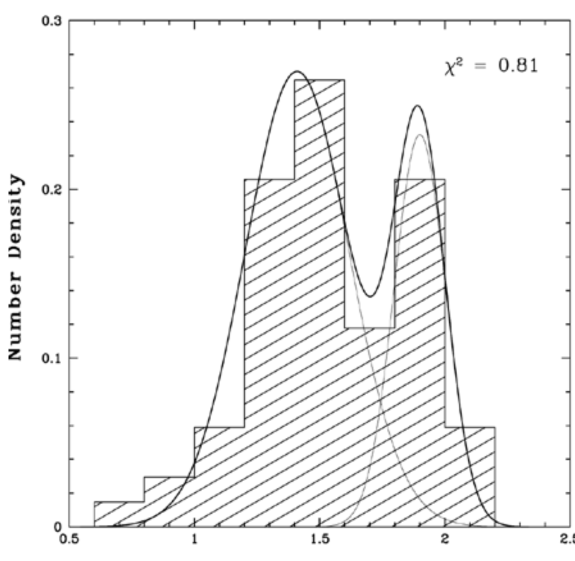

Figure 5. *The plotted "color" histogram of the NGC 5128 globular clusters is a proxy for metallicity. Two Gaussians fit the observations (hatched region) well, indicating a bimodal metal distribution.*

Kristin Woodley (then at McMaster University, Ontario, Canada) and colleagues used GMOS on Gemini South to measure the age and metallicity of nearly 200 globular clusters in the inner 15 kiloparsecs of the halo of the nearby giant elliptical galaxy NGC 5128 (Centaurus A, see Figure 4). This location favors the bright globular clusters toward the galaxy's center, which are preferentially metal-rich and young, but it also includes representative metal-poor and older populations.

The team found that most of the globular clusters have ages greater than eight billion years, similar to those in the Milky Way. Two distinct populations are apparent in metallicity (Figure 5). Both of these groups typically show older stars, but among the more recently formed globular clusters, most are metal-rich.

The ratio of alpha elements to iron is greater than the solar value, which implies rapid star formation. Given that these data yield an upper limit on the fraction of metal-rich and young globular clusters in NGC 5128, the authors conclude that most of the star formation in NGC 5128's globulars occurred rapidly (though more slowly than those of the Milky Way) and early, with some smaller component of accretion or later star formation. The full results have been published in *The Astrophysical Journal* (K. A. Woodley et al., 2010, 708, 1335).

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by Eric Tollestrup

FLAMINGOS-2 Update

Figure 1.
Steve Eikenberry celebrating first light with FLAMINGOS-2.

In June 2009, FLAMINGOS-2, one of four new instruments coming to Gemini South, was shipped from the University of Florida (UF) to Chile, where it has been undergoing acceptance and commissioning tests on the telescope. As one can imagine, Stephen Eikenberry (principal investigator for FLAMINGOS-2, see Figure 1) and other team members were excited to see the first on-sky images splash across the screens at Cerro Pachón. A wider celebration occurred when the first fully processed images were e-mailed to other project participants, particularly those at UF, the National Optical Astronomy Observatory (NOAO), and Gemini. Mosaic, multi-band images of the Galactic Center and the Tarantula Nebula (see Figures 2 and 3) are just a taste of the great things we expect from FLAMINGOS-2 once it is released to the Gemini community. The occasion also served as an impromptu, though poignant, tribute to the contributions made by the original P.I., Richard Elston, who tragically passed away before he could see the fulfillment of his brainchild.

Fortunately, most aspects of the instrument have passed acceptance testing; however, several are not yet acceptable, are missing, or have failed. The initial exuberance is now tempered by a number of harsh realities, and final commissioning of FLAMINGOS-2 has been delayed while these issues are resolved. Because there is such widespread and intense interest within the Gemini community regarding this highly anticipated instrument, this article describes the current activities and plans to get FLAMINGOS-2 "up and going" and into the hands of our observers.

Failed HAWAII-2 Detector

FLAMINGOS-2's most critical problem is the failure of its HAWAII-2 detector, which worked in Florida but was damaged by the time it underwent the first warm test in Chile. The problem with the array is that a large portion of one quadrant is not functioning. As shown in Figure 4 (an image of pixel "aliveness"), a large section of the upper right quadrant, about 30 percent, has stopped working (dark right-angle area in the middle of the quadrant). Although FLAMINGOS-2 could still be used in imaging mode, albeit with diminished efficiency, the impact on multi-object spectroscopy (MOS) is more severe. In data taken in the MOS mode (see Figure 5), a substantial number of MOS spectra are affected. Given its current state, this detector array can only be rated as "engineering-grade" and is not suitable for general science observations.

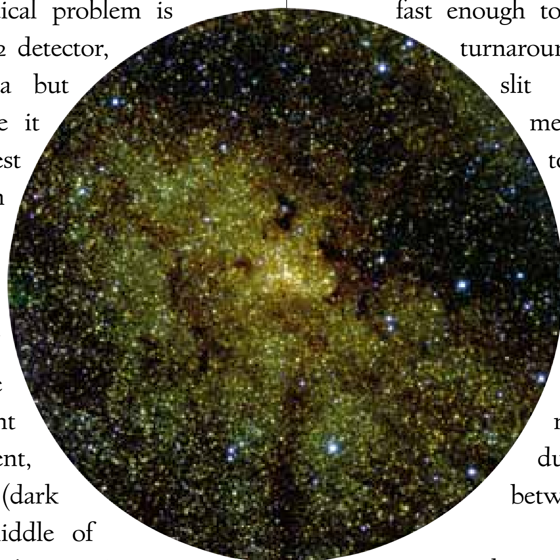

Figure 2.
Color composite, mosaic, first-light image of the Galactic Center.

Since we did not have a spare "science-grade" device, Gemini contracted with Teledyne Imaging Sensors to hybridize and test some of the last remaining HAWAII-2 parts. Teledyne completed the hybridization and initial factory testing in March 2010. Additional acceptance testing and the final selection of the replacement array will occur after a suitable facility for more thorough tests is identified and selected. Fortunately, the present Teledyne test data show that the hybridization of this latest (and perhaps last) batch of HAWAII-2 detectors went well and produced cosmetically very good devices (see Figure 6).

Other Key Issues Being Addressed

Another critical issue affecting FLAMINGOS-2 is the inability to thermally cycle the MOS dewar fast enough to accommodate the required turnaround time for changing MOS slit masks. Thermal clamp mechanisms that are supposed to permit rapid warm up and cool down are not functioning as designed and need to be fixed or modified. The basic requirement is to be able to warm up the MOS dewar, replace the slit masks, and then cool it down during the daytime hours between consecutive nights.

Several mechanical issues need to be resolved. For example, the gate-valve baffle mechanism, critical for reducing the K-band background, does not work when the instrument is oriented in the vertical position. Some mechanisms exceed the maximum time allowed to complete a move, while other mechanisms are not reliable (loss of position, for example). It's anticipated that some of these issues can be corrected with improved mechanical alignment and adjustments of the mechanism parameters.

Figure 3.
Color composite, mosaic, first-light image of the Tarantula Nebula.

An important (but missing) capability is the R = 3000 grism. As some readers may recall, a crack in the original grism was discovered in August 2008 during acceptance testing at UF. Unfortunately, but not unexpectedly in the world of infrared optics, the grism vendor had problems procuring appropriate prism substrate material, which prevented a speedy replacement. The new replacement R = 3000 grism

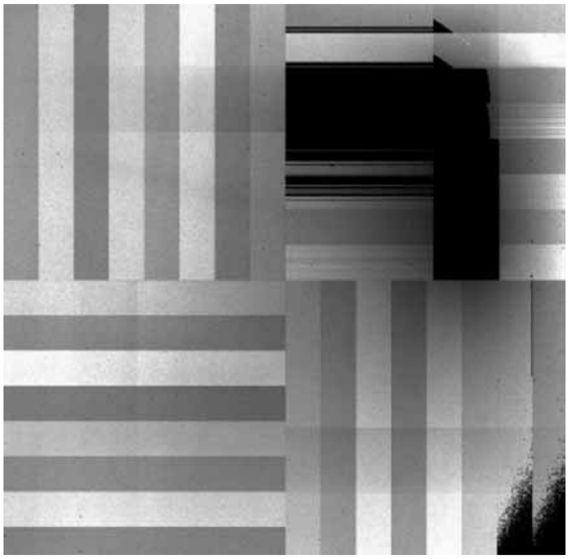

Figure 4.
Image of the existing HAWAII-2 array illustrating the failure.

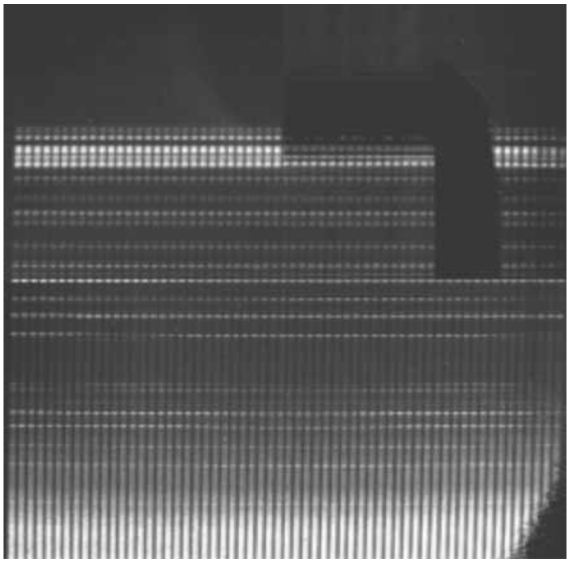

Figure 5.
Image taken in MOS mode. Individual spectra run up and down.

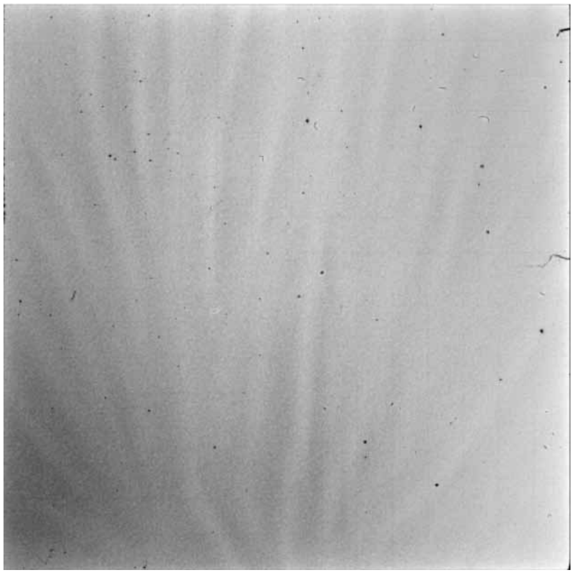

Figure 6.
Stretched image of the quantum efficiency in the K band for one of the candidate replacement arrays.

is now due to arrive at UF in April 2010 (as this issue goes to press).

Optically, there are larger aberrations than expected (primarily coma). Most likely this coma is a result of optical misalignment, which can be corrected.

Finally, there are vacuum and thermal stability anomalies. The vacuum pressure jumps and wanders depending on the location and orientation of the instrument as well as the telescope pointing direction, and it is correlated with internal temperature changes. Random vacuum leaks have also occurred, which, if left unchecked, could present a serious safety hazard.

The Path to Final Commissioning

Given these issues, Gemini decided to accept responsibility for FLAMINGOS-2 in January 2010 so that the combined resources of both the UF team and the Gemini staff can solve these issues in a more efficient, timely manner. Our initial plan of action, which started in February, consists of returning the instrument to La Serena, thoroughly re-evaluating each issue, and fixing each one, so we can resume commissioning in January 2011. In March, the instrument was transferred to La Serena where UF and Gemini staff are currently re-evaluating each sub-system. Unless new issues arise, the MOS cryostat problems will be addressed during the 2nd quarter of 2010, mechanism and camera issues will be tackled early in the 3rd quarter, the detector replacement and grism installation will start in the 3rd quarter and continue into early 4th quarter, and in December 2010 the final integration and testing will take place in the Cerro Pachón laboratory facilities.

Though we all may be disappointed by the unfortunate delay, these corrective actions are necessary. Moreover, the outcome of this activity will ultimately produce a robust, capable instrument that will allow the Gemini community to attack some very exciting and important problems in astrophysics.

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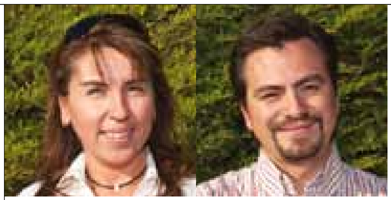

by María Antonieta García
& Manuel Paredes

Gemini South Laser Delivery

A Milestone in Adaptive Optics

Figure 1.
The Gemini South laser arrives at Cerro Pachón.

At the end of March 2010, nearly a decade of tireless effort culminated in the arrival of the 50-watt laser designed for the Multi-Conjugate Adaptive Optics (MCAO) system at Gemini South. "As one who's witnessed all the steps in the effort to build this laser, words cannot express my sense of pride and accomplishment to see our new laser finally home on Cerro Pachón," wrote Gemini Director Doug Simons in a letter to staff.

The laser, designed and built through a contract with Lockheed Martin Coherent Technologies, is currently (April 2010) undergoing testing at the instrument lab on Cerro Pachón. Once the 1.5 ton, (1.3- x 3.6- x 1.1-meter) laser bench enclosure and the 1 ton, (2.1- x 1.3- x 1.0-meter) laser electronics enclosure are installed and operational on an extension of the altitude platform of the Gemini South telescope, the orange-colored laser beam will bounce off a series of mirrors attached to the structure of the telescope, forming the system of the beam transfer optics (BTO). A laser launch telescope (LLT) located behind the secondary mirror then propagates the laser beams (there are five separate 10-watt beams) into the sky. At about 90 kilometers up, the laser light encounters a layer of sodium in the mesosphere. The laser light excites the sodium, causing it to glow and forming five laser guide stars (LGS). These allow the Gemini Multi-Conjugate Adaptive Optics System (GeMs) to achieve an unprecedented well-corrected 2-arcminute field-of-view, up to 70 percent sky coverage at 30° galactic latitude and Strehl ratios between 45-80 percent in the 1-2.5 microns range. For more technical specifications, see the Gemini Future Instruments page at: http://www.gemini.edu/node/11355

Senior Laser Engineer Céline d'Orgeville oversaw the construction and installation of the nearly US$5 million laser. Assisting in the delivery, installation, and commissioning are Cerro Pachón Site Manager Diego Maltés, Deputy Chief Engineer Mike Sheehan, Systems Engineer Gelys Trancho, Laser Support Engineer Vincent Fesquet, and many other Gemini staff. The final installation and testing will give Gemini South

Figure 2.
Gemini South and Lockheed Martin Coherent Technologies staff work together to on the laser in the Cerro Pachón instrument laboratory in Chile. Vincent Fesquet in the foreground, followed by Jared Roush and Nathan Rogers in the background.

unique capability. "No other laser guide star facility can produce five sodium laser guide stars," said Céline d'Orgeville. "This definitely opens up new and exciting opportunities for science."

Site Manager Diego Maltés oversaw the arrival of the 5.1 tons of packaging in Santiago and its transport to Cerro Pachón in March 2010. "I'm sure that the success of this operation was the result of good planning, excellent coordination between all involved, and the existence of procedures for transfer and subsequent installation in the Cerro Pachón instrument lab clean room," said Maltés.

Although all observatory departments were involved in the laser facility installation, its construction, implementation, and subsequent operation are mainly the responsibility of engineering and adaptive optics team members—among them Maxime Boccas, Felipe Daruich, Gelys Trancho, Céline d'Orgeville and François Rigaut (Adaptive Optics Senior Scientist). According to François Rigaut, the fact that Gemini South has this laser opens up new horizons in Gemini science. "We will provide an angular resolution 10 times better than the current one, which means that we will be able to see 10 times more details in the images," he said. "This will allow us to detect very faint objects with very weak light, and will have practical applications in such diverse areas of astronomy as stellar evolution, formation, evolution and chemical composition of galaxies, star-forming regions, and planetary nebulae, among others."

Laser propagation into the Chilean skies will also require cooperation with organizations outside of Gemini Observatory. For example, special authorization by the Directorate General of Civil Aeronautics of Chile and the U.S. Laser Clearing House is required.

It is expected that the laser will be moved from the Cerro Pachón instrument lab and mounted on the telescope structure in May 2010. Commissioning of the Gemini South Laser Guide Star Facility will begin in mid-2010.

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by Katherine Roth

Updates to GMOS-N

the Workhorse Optical Spectrograph at Gemini North

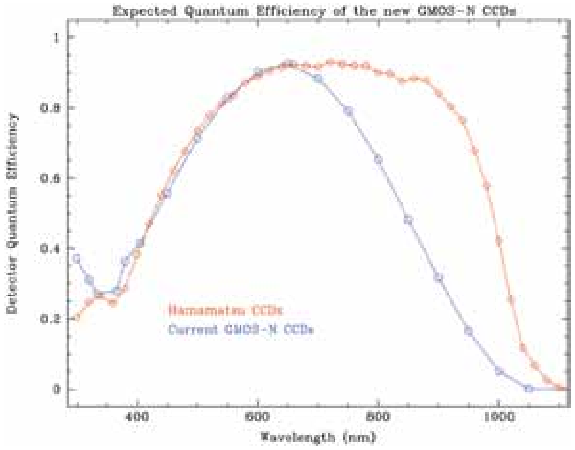
The Gemini Multi-Object Spectrograph at Gemini North (GMOS-N) has been steadily collecting optical spectral and imaging data for the Gemini community since October 2001. During those eight and a half years, there have been remarkably few major problems with the instrument as it has proved to be very reliable. However, there have also been relatively few upgrades or additions to the capabilities, with one notable exception being the highly successful (and very popular) Nod & Shuffle mode commissioned in August 2002.

We are very happy to announce several new improvements for GMOS-N. The upgrades started in Semester 2009B with the addition of five new narrow-band filters to the GMOS-N filter complement. But the big news will be the installation and commissioning of three new, deep-depletion, red-sensitive CCDs which is expected to be completed before the end of the year.

These detectors, purchased from Hamamatsu Photonics and currently being integrated into a new GMOS-N focal plane assembly at the Herzberg Institute of Astrophysics (HIA), will greatly enhance the GMOS-N sensitivity and extend the scientifically useful wavelength range all the way out to ~1.07 microns. In addition, two more broad-band filters will be purchased to allow imaging in this new wavelength range hitherto unavailable to GMOS-N users. Following is a description of both the CCD and filter upgrades.

Red-sensitive CCDs: The charge-coupled devices, already in hand, are by the same manufacturer of the detectors currently installed in the Subaru Telescope's Suprime-Cam Instrument. These CCDs have significantly better sensitivity compared to the first generation E2V CCDs in GMOS-N, particularly redward of 750 nm, with the quantum efficiency only falling below 5 percent at 1.07 microns (Figure 1). The focal plane assembly, integration, and detector testing is currently underway at HIA in Victoria, British Columbia.

Figure 1.
Typical quantum efficiency expected for the new GMOS-N CCDs (red) compared to that of the first-generation GMOS-N E2V CCDs (blue). Data for the new CCDs provided by Hamamatsu Photonics are typical for these detectors at an operating temperature of -100 degrees Celsius. The actual QE curves for the GMOS-N detectors will be measured as the detectors are characterized at HIA and so may change slightly from the figure given here. The new detectors are expected to have about the same or greater QE than the current detectors, particularly longward of 750 nm, with slightly lower QE shorward of 400 microns. The QE of the Hamamatsu CCDs falls below 5 percent at ~ 1.07 microns, compared to 1.0 microns for the E2Vs.



We fully anticipate being able to continue to offer these detectors with Nod & Shuffle, which will be very important for the new far-red wavelength GMOS-N spectral capability. The imaging field of view will remain unchanged at 5.5 x 5.5 arcminutes, but the simultaneous spectral coverage should be about 10 percent greater than with the current detectors. This is owing to the slightly larger physical size of the individual pixels (15 microns as opposed to 13.5 microns) while retaining the same number of pixels in the spectral array. The pixel size, 0.081 arcsecond/pixel, will still over-sample the optical seeing on Mauna Kea even in the best conditions.

These detectors have already been offered to the user community, although only for a right-ascension range limited to the last part of semester 2010B, as the delivery date of the new focal plane is still subject to modification.

Updates and further information regarding the characteristics of the new detectors (as it becomes available) can be found on the GMOS-N public webpages:

http://www.gemini.edu/sciops/instruments/gmos/imaging/detector-array/gmosn-array-hamamatsu

New Filters: In semester 2009B, we were able to offer to the community five new narrow-band filters with GMOS-N. Three of these duplicated the set already available with GMOS-S (OIII, OIIIC, and SII), and two are new capabilities now available with both GMOS-N&S (HeII and HeIIC). These filters allow users to map line emission in our galaxy (and beyond), including star-forming regions, planetary nebulae, supernova remnants, and the hottest, youngest stars known to exist (Figures 2 and 3).

Later this year we will be purchasing Z and Y filters for GMOS-N. These filters will match the specifications for the Z and Y filters currently installed in the UKIRT's WFCAM instrument and those used in UKIDSS. The current z' filter in GMOS-N is actually a long-pass filter with a short-wave cutoff at 848 nm and the long-wave cutoff being provided by the CCD itself.

With the new CCDs, we require an actual Z band-pass filter in order to match the Sloan z' band-pass. The Y filter is similar to that installed in NIRI, but will provide imaging over a greater field-of-view although NIRI is expected to remain ~ 20 percent more sensitive in the Y pass-band than the upgraded GMOS-N. The z' long-pass filter will continue to be offered for both imaging and spectral applications.

Further details, and measured throughputs for the new Z and Y filters (when available), can also be found on the GMOS public webpages, linked here:

http://www.gemini.edu/sciops/instruments/gmos/imaging/filters

Gemini is pleased to be able to offer these enhanced capabilities to the Gemini community, and we look forward to the new discoveries that will be made with the new and improved GMOS-N.

What about GMOS-S, you may be wondering? Actually, there are CCD upgrades planned for it as well, but the details regarding the exact CCDs – whether the emphasis will be on improving the blue sensitivity or the red, and the timing – are still being finalized. Watch this space for more information, and happy GMOS observing!

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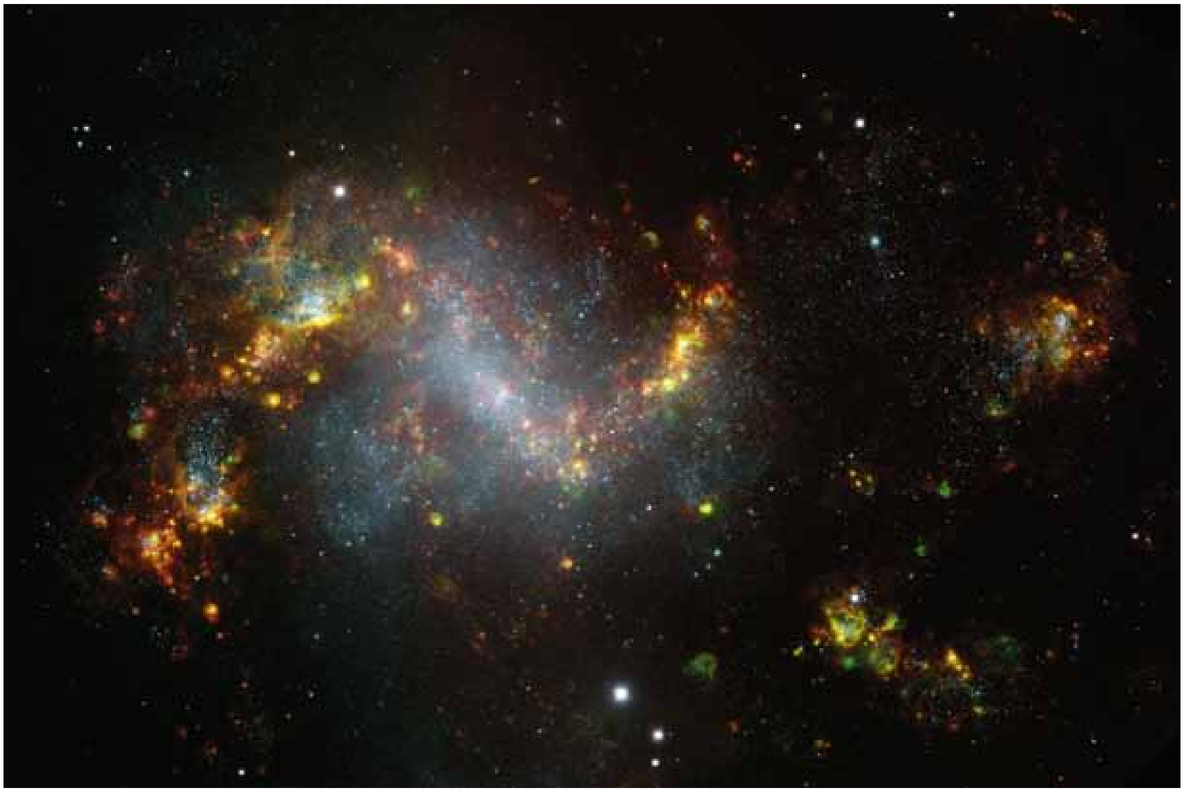

Figure 2.
Star-forming galaxy NGC 1313 as imaged using narrow-band filters on the Gemini Multi-Object Spectrograph on Gemini South. In the composite color image, red is H-α, blue is HeII and green is [OIII].

Figure 3.
Bi-polar nebula Sh2-106 as imaged using the new narrow-band filters on the Gemini Multi-Object Spectrograph on Gemini North. In this composite color image, red is Hα, violet is HeII, blue is SII and green is [OIII].

by Brian Walls

SOAR Mirror Coating

Figure 1. *Summit area of Cerro Pachón at sunset with Gemini South (right) and SOAR (left). Image obtained from the site of the future Large Synoptic Survey Telescope (LSST).*

In late October 2009, Gemini South once again opened its doors to the Southern Astronomical Research (SOAR) Telescope to re-aluminize its 4.3-meter primary mirror. SOAR was in the middle of an almost two-month shutdown where they planned to re-coat their primary, secondary, and tertiary mirrors, along with other improvement and maintenance activities.

Since the last time SOAR's mirror was coated in 2004 (also at Gemini), we have made great progress implementing the procedures and safety equipment used in the stripping and coating processes. Most of the improvements were first developed and implemented at Gemini North for the coating of the M1, M2-1, M2-3, and science fold mirrors, and we accepted this opportunity in order to migrate all that work to Gemini South in preparation for the SOAR mirror coating. Our focus on mitigating the risk of working under a suspended load led to the joint development of a support stand for SOAR's primary mirror, that would allow us to safely dry the underside of the 3,200 kilogram (7,000 pound) mirror. Many of the other processes and equipment improvements, such as critical ventilation improvements, will also be implemented during upcoming Gemini South coatings (later in 2010) that will include the primary mirror. This arrangement is a win-win situation for both telescopes.

The collaboration between SOAR and Gemini presented unique challenges for both observatories. Gemini provided coating and support services, over a period of two weeks, while maintaining full nighttime operations. To achieve this delicate balance, we agreed that Gemini would provide support only where the transport/stripping/washing/coating process interfaced with the Gemini South facility. Any services such as facility air, crane support, or effluent collection had a dedicated Gemini employee assigned to them. We also had two employees running the coating chamber, and one additional staff person who provided safety supervision and guidance. At any point we had a maximum of five Gemini employees supporting the process, leaving plenty of support staff for regular operations. SOAR on the other hand provided as many as 10-12 staff during intensive work phases, such as the transportation, stripping and washing processes. All of this required careful coordination and open communication, since we were using two groups that rarely work together, and with a key optical element that is essentially irreplaceable.

Figure 2.
SOAR optical engineer Roberto Tighe inspects the primary mirror from the central hole (inset), a position that he would later take during the stripping of the mirror. After the stripping of the old coating and washing the primary mirror the SOAR engineering crew must dry the underside before it is lifted into the coating chamber. The custom built structure allows us to perform this operation safely, without working under a suspended load.

While the overall process was a success, we ran into problems while stripping and washing the primary mirror, as well as with the coating facility magnetron. After stripping and washing the mirror once, we noticed drying streaks and coating artifacts on the mirror. We then worked together with the SOAR team to implement the Gemini stripping and washing process, which has provided good results in the past. Following the second attempt at washing, we verified that the mirror was sufficiently clean and moved the mirror into the coating chamber. After troubleshooting the magnetron and making many test runs, we found that a small leak in the water coolant lines had left the target "poisoned." This led to a lower than expected reflectivity and poor cosmetics on test surfaces. After removing the target and thoroughly cleaning it, we successfully applied the 90-nanometer, thick aluminum coating within the expected reflectivity range, and with very good cosmetics.

After spending nearly two weeks at the Gemini South telescope, the SOAR primary mirror was transported back down the road on November 3rd. Gemini staff was (once again) pleased to host our friends from next door, and provide support for this successful coating. This process was extremely helpful to us as well, and we feel confident that we will be much better prepared for the coating of our mirrors in the future, especially during the upcoming coating of the Gemini South primary mirror which is expected to occur in October of 2010.

We look forward to receiving the SOAR mirror again in about five years, when their primary mirror once again starts the 300-meter journey up the road to our Gemini South coating facility.

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by María Antonieta García

AstroDay Chile 2010

Figure 1.
AstroDay Chile 2010 allowed learners of all ages to participate in the exploration of the universe, from manned space flight to the discoveries at the astronomical observatories throughout Chile.

On January 23, AstroDay Chile 2010 attracted more than 2,000 local residents from La Serena and surrounding communities. The free event, organized and coordinated by the local outreach offices of both the Gemini Observatory and the University of La Serena, continued the successful annual program in a new venue, and attracted new audiences.

This year's event brought excellent participation by science staff from numerous observatories and research centers throughout Chile, tourist observatories in the region, and from Colombian as well as Chilean universities that offer degree programs in astronomy and physics.

A day-long schedule of oral presentations on general astronomy for families allowed local observatory scientists to delve into such diverse topics as dark matter, astrobiology, and technology in modern astronomy. At the same time, StarLab planetarium shows were being offered every hour. This year we also had two hands-on workshops that were taught by Colombian physicist and professor Cristian Goez, who amazed children and teenagers with interactive spectroscopy and rocket-making/launching demonstrations.

Figure 2. *Professor Carmen Gloria Jimenez from Universidad de Concepción shares her stories about teacher's Space Camp.*

The all-day event, held at the outreach center of the University of La Serena (Casa Piñera) attracted a wide range of attendees. People were able to participate in a more personal and at a deeper level than in previous years thanks to a ticketed admission that regulated the number of visitors throughout the 10 am – 10 pm event. According to Gemini South Deputy Director Nancy Levenson, "In prior years, AstroDay has attracted as many as 5,000+ visitors. But, this year the objective was to provide an improved experience with better quality interactions with each individual. This is why we decided to hold a much smaller event."

Figure 3. *AstroDay Chile 2010 was held from 10 am until 10 pm which allowed for evening observing with Galileoscopes made as part of the International Year of Astronomy.*

Representatives from 17 institutions (including those in Colombia, Argentina and Brazil) shared their research activities with visitors, encouraging everyone to get a closer look at astronomy from many different perspectives. The exhibit space featured beautiful images from the display "From the Earth to the Universe" (produced for the International year of Astronomy) and were later shown in many areas of Coquimbo during the months of February and March 2010.

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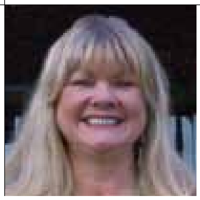

by Janice Harvey

Journey Through the Universe 2010

Figure 1.
Gemini's software engineer Angelic Ebbers teaches an eights grade class at Hilo's Connections middle school.

Journey Through the Universe (JTtU) is a national science education initiative that engages communities of students, teachers, families, and the public using education programs in Earth and space sciences as well as space exploration to inspire learning. The initiative promotes sustained science, math, and technology education, and is a celebration of exploration and the joys of learning. Developed by the National Center for Earth and Space Science Education (NCESSE), *JTtU* provides a window on the true nature of science and the lives of modern-day explorers, with special emphasis on what is known about our world and the universe, and also how it has come to be known.

Gemini Observatory continued its leading role in organizing Hawaii's sixth year of *JTtU*. The program captured a broad audience, including more than 5,600 students in 17 schools. Thirty-five of our fifty-five *JTtU* astronomy educators were able to visit 286 classrooms and serve as role models for the next generation of scientists and engineers. Two family science events, held at the ʻImiloa Astronomy Education Center and Borders Book Store, were attended by more than 3,000 people. The business community continued its ongoing support of the nationally recognized *JTtU* program by providing funding and participating in a thank-you celebration hosted by the Hawaiʻi Island Chamber of Commerce.

This year's *JTtU* theme was, "Human Presence in Space," and our workshops gave teachers the tools and training they needed to conduct powerful lessons in the classroom that are relevant to the Hawaiʻi State science standards curriculum. Teachers participating in this year's training also received a Galileoscope along with lesson plans courtesy of Gemini and the Thirty Meter Telescope.

Figure 2/3. *During a Journey Through the Universe classroom visit, students learn about optics and lensing by measuring the focal length of several lenses and learning how telescopes are built.*

Due to state budget constraints, local schools had one less instruction day per week for most of the school year. The *JTtU* scientists were able to provide relevant science, technology, engineering, and mathematics (STEM) education to the students. Christine Copes, master teacher from Waiakea Elementary School stated, "Since the inception of No Child Left Behind, science education, especially at the elementary school level, has taken a back seat to those tested content areas of mathematics and language arts. One program that has provided some much needed science content is *JTtU*. The program combines standards-based modules (complete with lessons for different grade levels) visiting scientists who are able to awaken students' curiosity about space science, family science events that include hands-on science activities, presentations from experts in the astronomy field, and wonderful access to local astronomy opportunities. This exceptional program is a truly unique school and community event that inspires thousands of students and their parents with the wonders of space science. Our community and, especially our students, are very fortunate to be participants in this incredible Journey!"

Journey through the Universe in Hawai'i has been recognized as the flagship national program in the United States. Throughout the year, *JTtU* presentations have been made at Astronomical Society of the Pacific meetings, Project Astro/Family Astro and Communicating Astronomy with the Public conferences. Much interest has been shown in recreating the *JTtU* program not only in other states throughout the U.S., but also in countries around the world.

We look forward to *JTtU* 2011 and the continued outreach it fosters for many years to come. For more information on the *JTtU* program, please go to our website at: www.gemini.edu/journey

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by Silas Laycock

Stéphanie Côté:
Canada's Face of Gemini

It was an inky black, perfect night on Mauna Kea, but things were tense in the Gemini control room. Observing with OSCIR (Gemini's first-light, mid-infrared instrument), astronomer Stéphanie Côté was fighting every step of the way to image young stellar nurseries, and nothing seemed to be going right. These were the dark days before the advanced Observing Tool software streamlined Gemini's operations, to provide today's seamless interaction between instrument, mountaintop observer, and principal investigator thousands of miles, and many time zones away. The thin air at over 4,000 meters wasn't helping, and her mind was clouded.

Some time in the small hours of the night, it became necessary to "tune" (reshape to infinitesimal tolerances) the primary mirror, and Côté took the opportunity to ascend five floors to the dome while this operation was performed. The telescope was inclined almost to the horizon, and Côté vividly recalls the breathtaking sight, "It was totally dark in the dome, and the entire Milky Way and Jupiter were reflected in the great mirror, from horizon to horizon," she said. "I could see Jupiter jumping by distinct but almost imperceptible twitches as the actuators behind the mirror moved. Needless to say, all the frustrations of the night were forgotten."

That was Stéphanie Côté's first time observing at Gemini in 1999, and her most memorable experience in astronomy. Now head of the Canadian National Gemini Office (NGO), she returns to Mauna Kea and Cerro Pachón twice a year and is continually floored by the pace of improvements in Gemini operations—an experience she likens to "a mother seeing her child grow."

In her NGO role, Côté is a familiar face to Canadian astronomers, for whom Gemini is "the" facility for cutting-edge astronomical discovery. She is also well known to the Canadian public from her frequent media and radio interviews. Her job includes soliciting science proposals, organizing time allocation committees, helping Canadian astronomers design their observing programs, and making sure their results reach a wide audience.

Côté has been instrumental in ensuring that the Gemini telescopes are accessible to all, running the highly popular public-time programs, which have allowed amateur astronomers, high-schoolers, and even elementary school pupils, to take pictures with the Gemini telescopes. Côté feels strongly that outreach should be a fundamental part of what professional astronomers do; this sentiment is echoed in Gemini's statement of purpose: *Exploring the Universe, Sharing its Wonders.*

Côté is based at the Herzberg Institute of Astrophysics (HIA) in British Columbia. As the public face of astronomy in Canada, Côté knows the value of social and communication skills and clearly thrives on the varied challenges. But, as she admits, "Saying 'no' to

(Opposite page) Stéphanie Côté enjoys the outdoors in Victoria, British Columbia, Canada with her husband Domenico Trombetta and son Fabiano.

Photograph by Robert Leon

a famous professor, that their proposal did not make the grade, can still be intimidating, as can explaining to a recognized expert why their observing plan needs to be restructured. It's the support astronomer or NGO's role to help Gemini's user community to get the best performance possible from the telescopes and instruments."

By the time Gemini's staff ever sees an observing plan, Côté and her team of four additional astronomers (or another partner country's NGO) have devoted hours or days to correcting, reshaping, and optimizing it. The only goal is to deliver data that will enable the principal investigator to make those seminal discoveries touted in observing proposals!

Like many readers of *Gemini*Focus, Côté was bitten by the science bug early on, when, as a preteen, she pored over every astronomy book and article in her local library. After reading Steven Weinberg's *The First Three Minutes* at age 11, she was hooked. Côté went on to get her degree in physics at the University of Montréal. By that time she was concerned about the job market and briefly considered a career in the telecoms or solar-energy sectors; both fast-growing and with the promise of work close to home. Luckily for Gemini, during her second semester Côté took an extra astronomy course taught by Tony Moffatt; it turned out to be the highlight of each week and sparked Côté's fascination with dark matter.

Upon graduating, Côté started a master's degree with Claude Carignan, moving to the Netherlands to join a research group that was leading the way in characterizing dark matter by studying the rotation curves of dwarf galaxies. With master's degree in hand, she decided to pursue a Ph.D. in Australia with Ken Freeman, a leading figure in dark matter research. Stéphanie's parents tried in vain to discourage her from following through with her plan. In fact, she says, "They told me astronomy is a dead end!" Not to be discouraged, Côté departed for the other side of the globe, with 20 Canadian dollars in her pocket and a fellowship from the Québec government.

Stéphanie shares a love of science with her siblings. Her older brother and sister are both engineers, and her eldest sister is a doctor. Although medical careers ran in the family, she was astonished to discover, while on a visit home during university, an early 20th-century photograph showing her maternal grandfather at the eyepiece end of the University of Vienna's Great Refractor. It turned out he was a Doctor of the Ph.D. variety, and an astronomer to boot; he raised his family on the Vienna Observatory grounds and Stéphanie's mother remembers playing in the dome as a child. Whether astronomy was in the blood or not, "Not knowing about this as a teenager probably prevented me from rebelling and going in a different direction!"

In Australia, Côté made Mount Stromlo Observatory the base of operations from whence she conducted a daunting observing campaign that formed the basis of her Ph.D. thesis: "*Dwarf Galaxies in Nearby Southern Groups.*" Shielded behind a typically unassuming title, the thesis presents key revelations about the role of dark matter in galaxy formation, drawn from its distribution in dwarf galaxies.

By measuring stars and gas in dwarf galaxies that are falling into two great clouds of galaxies (the Sculptor and Centaurus A groups), Côté and her supervisor Ken Freeman hoped to deduce whether the dwarfs contained enough dark matter for them to resist the pull of their massive neighbors. Côté found 32 dwarf galaxies by examining photographic survey images, and then went after them with more powerful optical and radio telescopes: the Siding Spring 2.3-meter, the Australia Telescope at Narrabri, the famous Parkes radio telescope (where she spent marathon 10-day shifts), and Siding Springs' venerable 40-inch, where she also spent innumerable nights.

"The dwarf galaxies are so faint, many below 24 magnitude/arcsecond^2 in the optical, that it can take more than a night to image them," Côté says. "But with Parkes, we could easily detect them in as little as 10 minutes, thanks to their vast clouds of hydrogen gas, invisible in the optical, but bright emitters of 21-cm radio waves." The radio observations enabled Côté to measure rotation within each dwarf galaxy due to Doppler shifting of the 21-cm wavelength. Mapping the Doppler shifts revealed that the dwarfs are rotationally supported, and are embedded in dark matter haloes up to 10 times more massive than all the stars and gas that can be seen with telescopes.

"At the time, everyone in the field was arguing whether the dark matter density profiles in dwarfs follow a sharp cusp within the core as simulations predicted, or a smooth core as observations seemed to suggest," Côté says. "We showed with many dwarfs, that there is no cusp, and that is now agreed to be a settled matter." Armed with such a fundamental breakthrough in dark matter, Côté won a prestigious European Southern Observatory (ESO) fellowship. Moving to ESO headquarters in Garching, Germany, is a time she remembers fondly, "We were 12 young postdocs, running around together like a big group of happy puppies."

With her unique dataset from Australia in hand, Côté went on to discover a new mystery in the Sculptor and Centaurus galaxy groups. Dwarf galaxies supposedly fell into two types: the "red and dead," which have been stripped of all their gas by close encounters with massive neighbors in the galaxy group; and blue star-forming dwarfs, which have somehow held onto their gas, perhaps because they entered the group only recently. However, a small fraction of the dwarfs in her sample fell into an oddball transitional state. They have the overall colors of red-and-dead galaxies, but somehow contain young star-forming regions.

Taking deeper images than ever before, the transition dwarfs seemed to be oddballs in their shape too—neither smooth red elliptical "rugby-balls," nor quite the irregular pancakes of the star-forming dwarfs. The next promising lead came from comparing the distances of the dwarfs to those of their nearest neighbors in the group, particularly the big ones. "We found that dwarf ellipticals are mostly close to big galaxies, dwarf irregulars are distant, and transition dwarfs are in the mid-range. There is a morphology-density relationship in all the nearby groups, similar to the Local Group, and furthermore transition dwarfs follow it too."

ESO assigned Côté as a support astronomer for the New Technology Telescope (NTT), observing remotely from the Garching control room. At that time, the NTT was a testbed for the coming VLT, charged with perfecting the nascent technology of active mirror control. Côté was assigned to the user group, (led by Dave Silva, now head of the U.S. National Optical Astronomy Observatory, NOAO) responsible for figuring out just what the future VLT observatory would be. There she guided remote observing and queue scheduling from mere concepts into robust and efficient operations that now power Gemini as well as the VLT.

In 1999, Côté joined Gemini just in time for first light. As one of the few Canadians with experience on the new generation of monolithic-mirror, 8-meter telescopes, she was a natural choice.

One problem in Sculptor/Centaurus still keeps Stéphanie up at night (although not literally anymore): those mid-range distances for the transition dwarfs are still too large for the giant galaxies to have even begun stripping their gas. Here Côté and Gemini are hot on the trail. If the transition dwarfs were stirred into life by passing giants, then she expects to see gradients in the ages, metallicities, and kinematics in the dwarfs that are completely different than those from recent mergers between smaller dwarfs. With her colleagues, Côté is now using GMOS to take spectra that will look for these gradients.

As you might expect from one living in British Columbia, home of this year's Winter Olympics, Côté used to ski "a lot." She also competed in ballroom dancing, which is where she met her husband—doing the Tango. The couple welcomed a son in 2007, at which point Côté traded her frequent mountaintop vigils at the telescope for the NGO leadership, and swapped skiing for a new outdoor pursuit of geocaching.

Her son, now three years old, loves searching for the bits of hidden treasure that geocachers hide and seek with handheld GPS units. "It makes our weekend hikes a whole lot more exciting for the little one," Stéphanie says. She also revealed that Mauna Kea has a couple of geocaches: "I couldn't resist going and finding them last month when I visited Gemini North, and no, I cannot tell you where they are!" Côté likes to add astronomy outreach goodies to the caches, so the finders may encounter Gemini DVDs, magnets, postcards, or key chains. She recently created a well-stocked geocache near the HIA; to find it, seekers must solve a series of constellation puzzles based on Gemini images to deduce the coordinates. This is just one more example of Stéphanie Côté's innovation in bringing astronomy to the public and making it exciting for a new audience.

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by Helen Sim

Stuart Ryder:

Outward Bound

It is a night in 1981. In the small city of Dunedin on the South Island of New Zealand, 14-year-old Stuart Ryder (today the head of the Australian Gemini Office) and members of the local astronomy club are making their way to their observatory for a meeting. Suddenly, Stuart sees "bright colored rays, a checkerboard pattern of light and dark patches," forming in the sky above them. Abandoning their meeting, Ryder and his friends spend hours imbibing a rare treat — the southern aurora.

That first sighting of the aurora affected Stuart profoundly. "It was just phenomenal," he says, recalling how its alternating brightness would ripple across the sky and then come back again. "I'd never experienced anything like that before, and I wanted to see more of it, and learn more about what caused it." In time, Stuart would set his sights even higher. The upper atmosphere "wasn't really high enough for me, I wanted to go further, see deeper," he says.

Stuart grew up in Dunedin, one of four children of David (a highway draughtsman) and Lorna (a secretary). He was born with glaucoma. Operations at six months of age were all that stopped him from going blind. Stuart fondly remembers the day he told his parents he wanted to become an astronomer; one of their concerns was that his eyesight wouldn't be good enough. But Stuart assured them: "They do it with computers these days." In the end, his parents were supportive: "They were happy just to see me do something that fired me up, because I was not the most outgoing as a kid."

Stuart's interest in astronomy was triggered by reading science publications at his high school library. "The things that fascinated me most were the star charts, and the descriptions of where the planets were, and what the Moon was doing," he remembers. "So I'd go outside at night and look for these things and realize, 'Hey, there is some order and logic in all this.' There are lots of things that are predictable, but there are also lots of things that are unpredictable."

Also in 1981, he bought his first telescope: a 3-inch Sportmaster refractor he'd seen in the window of a photographic shop in Dunedin. Stuart had saved up NZ$600 to buy it, working weekends at a small grocery store near his home. "I used that telescope for years. It was the next step in getting to know the universe. I even started making notes about what I saw and sketching it. I've still got my old logbooks somewhere," he says, noting that he had to sell that telescope to help pay his university fees.

But, Stuart was already moving on to larger instruments. The local astronomy club had a 12-inch reflector, which he used after meetings and on public-viewing nights.

(Opposite page) *Stuart takes a hike through bushland near his home on the Lane Cove River in Sydney, Australia.*

Photograph by Tim Wheeler

A little later, he ventured into astrophotography, using hypersensitized color film supplied by a friend in the chemistry department of the local university. As luck would have it, the first picture they took was of the Tarantula Nebula in the Large Magellanic Cloud on February 23, 1987: the date on which SN1987A, the brightest supernova since the invention of the telescope, was seen erupting in that very spot. Theirs was one of only two pre-discovery photos of the supernova. Although Ryder was not the first to spot SN1987A, he says the experience underscored the opportunities for making a discovery in astronomy.

Following his dream to be an astronomer, Stuart left Dunedin to attend the University of Canterbury in Christchurch, further north on the South Island—a first step in his growing quest to see more of the world. "And, astronomy has been very good to me in that sense. It's given me the opportunity not just to visit, but to live and work in many interesting locations overseas," he says.

Stuart's first overseas move was to Australia, when he took a summer vacation position at the Australian National University (ANU), in what is now the Research School of Astronomy and Astrophysics. By coincidence, he was analyzing spectra of SN1987A, identifying and measuring features. "It was a good experience, and that really set me thinking, 'I don't have to do my Ph.D. in New Zealand, I can go somewhere else.'"

At first he thought mainly about Northern Hemisphere institutions, but the southern sky "seemed a lot more ripe for exploration and discovery than the northern [sky]," he says. "I could have stayed in New Zealand, but that was a pretty limiting option back then, I felt, because our biggest telescope was only one meter in diameter, and we were just getting our first CCD camera. I wanted to get my hands on bigger telescopes. Aperture fever! And it's never really stopped."

Later, in his Honors year, Stuart applied to the ANU and was accepted into its program. For his Ph.D. thesis, he worked with Professor Michael Dopita on massive star formation in galactic disks. Along the way, he was also invited to collaborate on a research project using a newly built radio telescope, the CSIRO Australia Telescope Compact Array. During this time, he discovered supernova SN1978K, pinning down the date of the explosion from archival images. It was one of only a handful of "Type IIn" supernovae then known. He still makes radio observations of this object from time to time. "Given that it's one of the oldest of these objects, it's the one to keep watching."

One of the side benefits of working with Dopita, Stuart says, was learning to appreciate wine. On their trips to observatories, Dopita would take him to out-of-the-way wineries, which were too small even to have cellar door sales, "but Mike knew where to go," he says.

After ANU, Stuart took his first postdoctoral position with Ron Buta at the University of Alabama, studying resonance-ring galaxies. For his second postdoc, it was back to Australia: the University of New South Wales (UNSW) in Sydney wanted someone to work on a tunable filter for the infrared. (At the time, Stuart had no experience with infrared instruments, but he applied for the position anyway, and got it.)

Stuart's globe-trotting was not over. In 1997, he moved to Hawai'i to work in a combined position of telescope operator and research scientist for UKIRT. "It gave me the opportunity not just to visit but to work on Mauna Kea. The sunsets and sunrises were just fantastic, and the occasional green flash is something I remember very fondly." But after a couple of years, Stuart saw an opening at the Anglo-Australian Observatory in Sydney. "It had always been my ambition to work at the AAO, because they had the biggest telescope in Australia. And it seems that the AAO has always had one New Zealand astronomer on staff. It seemed only right that I should maintain that tradition." So in 1999 he returned to Australia.

With these moves between countries came shifts in the emphasis of Stuart's research. "I've moved from star formation in disks to resonance-ring galaxies; and then at UNSW I had to start work in a new area of infrared studies of star-formation regions; and then when I moved to Hawai'i, I started focusing more on the central regions of galaxies. Since I've come to Australia, to the AAO, I've actually started working more on supernovae." It makes life more interesting, he says, but has also made it harder to establish a profile in any one area.

Stuart's first direct experience with Gemini came in 2003, when he collaborated on observations of M83 made with a visitor instrument called CIRPASS on Gemini

South. Before that, in 2002, he helped the Australian Gemini Office make technical assessments of proposals: this was an unpaid, volunteer position. At the same time, he decided to redirect his research and support skills to better match the needs and opportunities of Gemini—for instance, moving away from HII regions towards circumnuclear star formation, "which is something you can only really do in the infrared, and at high-spatial resolution,"—and become more familiar with Gemini's instruments.

In 2008, Stuart became the Australian Gemini Scientist. Managing the Australian Gemini Office (AusGO) now takes two-thirds of his time; the rest he spends on his own research. "Managing AusGO is certainly an important milestone in my career. It's given me my first taste of managing people," he says, before confessing that the television comedy "The Office" has given him some great management tips!

The first Australian Gemini Project Scientist (and fellow New Zealander), Professor Warrick Couch of Swinburne University, remembers Stuart from his days as a post-doc at UNSW, saying he was "dedicated, reliable, and knowledgeable . . . a guy who contributes a lot to any environment." For Matthew Whiting, a colleague who also does technical assessments of Australian Gemini proposals, Stuart is, above all, reliable: "easy to talk to, and someone I can count on getting a response from."

Stuart has not lost his passion for watching the sky. That first sight of the aurora in Dunedin led to a taste for more. In 2002, he joined a trip to Alaska specifically with the hope of seeing the northern aurora, and was not disappointed: the sky performed every night of his visit. But his real passion now is chasing total solar eclipses. "It's an addiction," he says. After hearing the experiences of, and seeing pictures by, members of the astronomy club in Dunedin, Stuart thought, "Wow! This is something I have to see."

Stuart's first experience came in 1991, with totality occurring over the Baja peninsula. "Although it was six and a half minutes, which is about as long as eclipses can be, I knew that wasn't enough: I had to see another one. Nothing can prepare you for what it feels like." The change in temperature, the change in quality of the light, "it's all very unworldly," he says.

Stuart has now been on eight eclipse expeditions, six of which were a success. "I let Mother Nature decide where I'm going to take my major holiday every two or three years." Eclipse hunting has taken him to Turkey, twice; to the Atacama desert of Chile; to the Caribbean; to the Australian outback; across Russia, to Mongolia; and most recently, to China. Now he's eying northern Australia in 2012.

When he travels, Stuart likes to collect "tacky fridge magnets—silly, pointless ones," he says. His collection now covers two sides of a fridge, but the rate of collecting has tapered off, because "after a while, it became hard to find ones that were tacky enough."

In between eclipse trips, Stuart enjoys smaller-scale pleasures. One of them is bushwalking (hiking). "I've done the Routeburn walk in New Zealand, and I'd like to go back and do one of the other great walks. The Milford Track, or the Tonagariro circuit in the North Island would be nice." Sydney is also blessed with many areas of bushland on its borders, and even around its harbor. Ryder likes to take visitors on a bushwalk between the suburbs of Seaforth and Manly. "I think it's one of the great walks of the world, because it allows you to see so much: parkland, harbor views."

He also likes to have people over for a barbecue; sometimes he breaks out his new 3 1/2-inch apochromat for some impromptu backyard viewing of the Moon and planets. The refractor was a present from his astronomy club friends in Dunedin when Stuart and his wife, Marilena, married in 2006.

Although Stuart would like to spend some part of his future in New Zealand, perhaps helping to foster astronomy there, "at the moment, the opportunities for me in Australia are much greater. Leading the Australian Gemini Office is something I've always thought of as a major milestone in my career. Astronomy has been very good to me over the years, and I've tried hard to put back into that."

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GeminiFocus

Cerro Pachón from the future Large Synoptic Survey Telescope (LSST) site, providing a spectacular view of Gemini South and SOAR with the backdrop of the Andes.

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