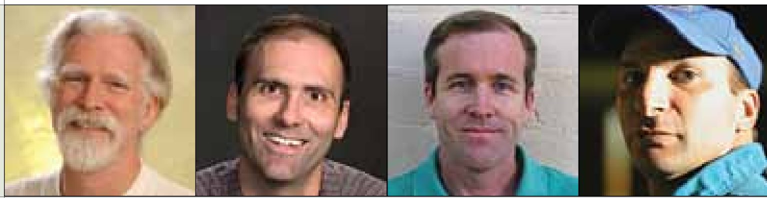

Steve B. Howell, Elliott Horch, Mark Everett, and David Ciardi

High-resolution Optical Speckle Imaging at Gemini North

A visitor instrument at Gemini North takes the highest-resolution, ground-based optical image ever made of the Pluto-Charon system. Results have ramifications on both the study of the not-quite-a-planet Pluto system as well as the search for exoplanets.

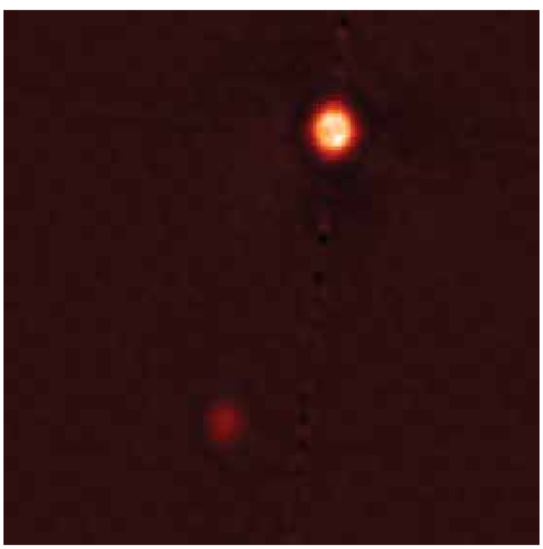

Figure 1.
The reconstructed image of Pluto and Charon obtained at 692 nm. In the image, north is up, east is to the left, and the image section shown here is 1.39 x 1.39 arcseconds across. No pixel smoothing has been applied to the image.

"Clearly the best!" It's the oft heard phrase about the atmospheric clarity and seeing on Mauna Kea, the purported first-born son of Wākea and Papa, according to Hawaiian lore.

Well, we are here to tell you, we agree. Mauna Kea is a premiere observing site, especially for speckle interferometry, a technique that employs a sequence of short-exposure "snapshots" to obtain images at a telescope's diffraction limit. In July 2012, a generous allocation of Director's time allowed us to bring our Differential Speckle Survey Instrument (DSSI), a speckle camera, to Gemini North as a guest-instrument. When coupled with the superb 8-meter optics of Gemini, that dual-channel instrument, which employs an electron multiplying CCD sensor (EMCCD) with no readout noise, allowed our team to produce diffraction-limited shots of Pluto and its largest moon Charon. At an angular resolution of 20 milliarcseconds (+/-3-4 mas), these are the highest-resolution, ground-based optical images yet achieved for the Pluto-Charon system (see Figure 1).

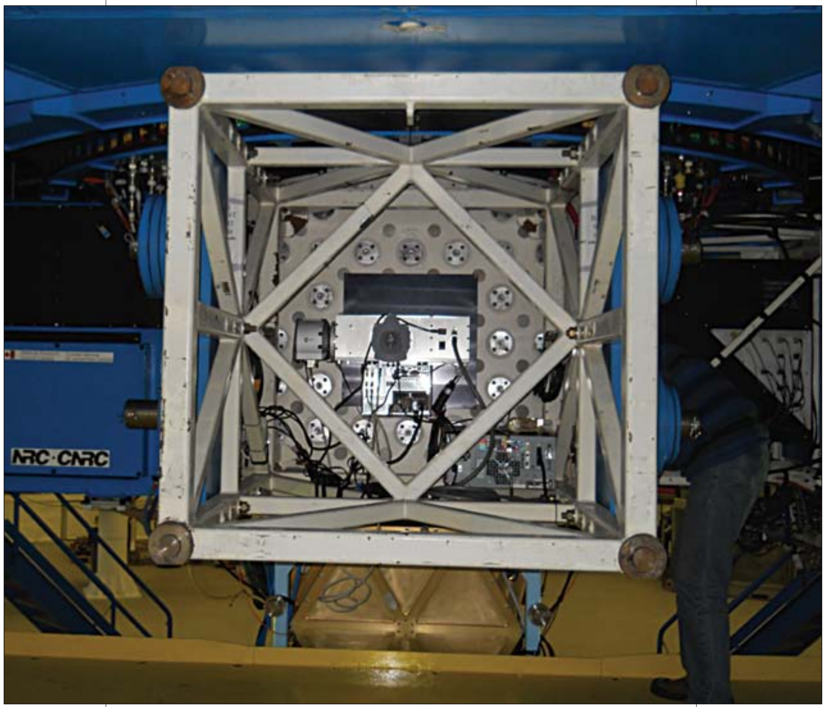

Figure 2.
DSSI mounted on the side port at Gemini North. The instrument (top silver box with two EMCCD cameras attached –– one on the left and one towards the viewer) is surrounded by the larger standard Gemini instrument cage enclosure. The small box attached underneath is the instrument control computer.

The Scientific Purpose

You can see the DSSI mounted on a side-looking port of Gemini North in Figure 2. For scale, it's about the size of a carry-on suitcase. When we arrived at the telescope, the mounting, focus, and computer connections and controls worked essentially without a hitch. The Gemini day-crew members were super at their jobs and made the setup process painless. But finding enough small straps and bolts to lift the 35-kilogram instrument with the dome crane, and then balancing it with the three other side-port monster instruments, proved to be a fun challenge.

The scientific purpose of the observing run was to use our high-resolution imaging ability to help the NASA Kepler spacecraft mission and the European Convection, Rotation and Planetary Transits (CoRoT) satellite mission to validate small planets orbiting other stars. Both of these missions provide time-series light curves of stars, which can reveal transit-like signals in them. They both also rely on ground-based follow-ups for exoplanet confirmations. One of the largest false positive sources masquerading as an exoplanetary transit event are background eclipsing binaries or a variety of other variable stars. By background, we mean a star that's nearly co-aligned with the assumed exoplanet host star. Its light mixes in with the target star, mimicing a transit-like event. High-resolution imaging allows us to examine the area of space very near a potential host star and detect (or not) these confounding troublemakers.

Kepler, for example, has broad point-spread functions covering 1-2 pixels, with each one spanning 4 arcseconds. Thus, the parameter space of close neighbors to a typical 12^{th}- to14^{th}-magnitude target star is large, both in area and in magnitude. Therefore, one must try to examine the background sky as close as possible to the target star. It also requires looking as deep as possible in magnitude. Since Kepler and CoRoT both image in visible light, we performed our speckle work at optical wavelengths as well, to best match their bandpasses. Doing so also helps in confirming or denying a target as a good exoplanet candidate.

As a demonstration of the power of combining DSSI with Gemini, our team succeeded in obtaining the sharpest ground-based snapshots ever obtained of Pluto and Charon in visible light (see Figures 1 and 4). While this result only hints at the exoplanet verification power of a large state-of-the-art telescope when combined with speckle imaging techniques, the data also verified and refined previous orbital characteristics for Pluto and Charon while revealing the pair's precise diameters.

The Pluto-Charon result is of timely interest for scientists wanting to understand the or-

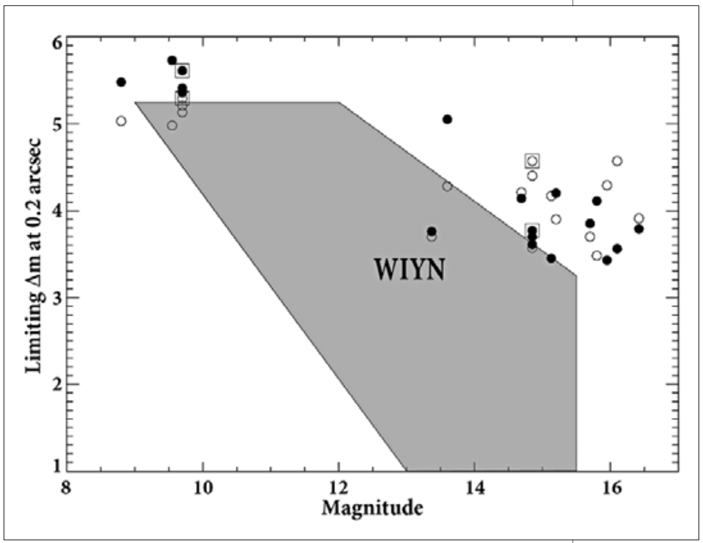

Figure 3.
Summary of the Gemini-limiting magnitude at 0.2 arcsecond and the target brightness we can reach with our speckle camera. Filled circles are the results at 692 nm, and open circles are the results at 880 nm. The boxed points are cases where results from two nights were combined. The shaded area marks the region of most points in the same plot for WIYN telescope data. All points are marked at the estimated 5-sigma limit at a separation of 0.2 arcsecond. Doubling the observation time would move points upward by 0.25 magnitude, and if 3-sigma limits are desired, all points would move upward by 0.55 magnitude.

bital dynamics of this pair for the 2015 encounter by NASA's New Horizons spacecraft.

DSSI: The Instrument

The DSSI consists of an optics box that contains the field lens, beam splitter, and filters. It simultaneously sends the light to two iXon EMCCD cameras. The filters and beam splitter are changeable, and due to their small size, relatively inexpensive. A PC based software program runs both the instrument and the two cameras. Typically, we observe in the visual through infrared bands, although any optical band is possible, being constrained only by the CCD quantum efficiency profile.

Speckle data are obtained through very narrow band (~40 nanometers) filters centered on the wavelength of interest. EMCCD readout generally consists of a windowed sub-region, covering 2-3 arcseconds on a side at a plate scale of ~0.01 arcsecond per pixel. DSSI can also perform astrometry to at least the 0.9 mas-level in a 3-minute observation and provide a photometric measurement of the stars observed to +/- 0.1 magnitude at Gemini North.

We have used our speckle camera in a broad survey of exoplanet candidate host stars employing the WIYN telescope in Arizona and now Gemini North. At WIYN we examined the bright star sample and used Gemini North for a more selective program aimed at the smallest, Earth-like exoplanet candidates orbiting within their habitable zones.

Figure 3 shows a summary of our typical observations at the two telescopes. Gemini North provides higher resolution (*i.e.*, closer-in views near the target star) and deeper limiting magnitudes; Gemini's superior telescope size, optics, and high-altitude location also allows us to observe fainter target stars than at WIYN. While our engi-

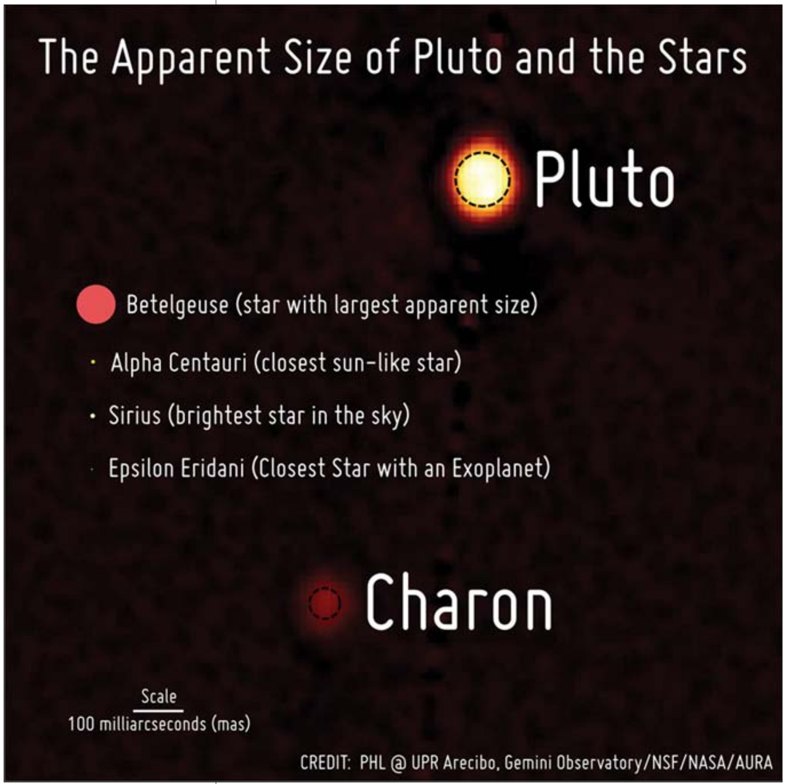

Figure 4.
The reconstructed image of the Pluto-Charon system with their angular sizes drawn (dotted circles inside "glare") along with the angular sizes of four known stars. Note that our imaging system on Gemini can also resolve the largest stars.

neering run at Gemini was short, we tested our speckle imager on a wide sample of potential exoplanet host stars from the CoRoT and Kepler missions.

When mounted on Gemini North, DSSI can reach to deep limiting magnitudes and observe very faint target stars. Both of these factors represent new limits for any speckle imaging observations and promises to provide a powerful tool for the validation of Earth analogues.

To show the variety of possible programs that would benefit from the high-resolution images available with DSSI and Gemini North, our fully-resolved observations of Pluto are shown in Figure 4 compared to the sizes of some well-known stars. Pluto's moon Charon, has a smaller angular size than the star Betelgeuse, highlighting the possibility of using our camera system to resolve and study surface details for large stars and other resolved objects, as well.

Given the great potential for a number of types of high-resolution images, DSSI is likely to return to Gemini North for observations in mid-2013 for general user programs from across the international Gemini partnership. Any such arrangement will be announced along with the call for proposals for Semester 13B, in February 2013.

References:

Howell, Steve B., *et al*., *The Astronomical Journal*, 42: **1257,** 2011

Howell, Steve B., *et al*., *Publications of the Astronomical Society of the Pacific*, **124:** 1124, 2012

Horch, Elliott, *et al*., *The Astronomical Journal*, **141**: 45, 2011

Horch, Elliott, *et al*., *The Astronomical Journal*, **144:** 165, 2012

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