SPECKLE IMAGING AT GEMINI AND THE DCT

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RESUMEN

Se describe un programa de observaciones de interferometría de motas con los telescopios "Discovery Channel Telescope (DCT)" y Gemini Norte y Sur. Se utiliza el instrumento "Differential Speckle Survey Instrument (DSSI)", construido en la Southern Connecticut State University en el año 2008. DSSI es un sistema de puerta dual que registra imágenes de manchas en dos colores simultáneamente, y produce imágenes limitadas por difracción hasta una magnitud de $V \sim 16.5$ en Gemini y hasta $V \sim 14.5$ en el DCT. De los varios proyectos que se realizan en estos telescopios, se le dará énfasis a tres de ellos: El primero es un seguimiento en alta resolución para las misiones de exoplanetas *Kepler* y *K2*, el segundo es un estudio de binarias espectrosópicas de baja metalicidad con el propósito de resolver estos sistemas y determinar sus órbitas visuales para, eventualmente, efectuar determinaciones de masa, y el tercero es un estudio sistemático de enanas de tipo tardío cercanas, para las cuales la fracción de multiplicidad puede ser medida directamente y comparada con la de las enanas de tipo espectral G. Se discute el estado actual de estos proyectos, y se presentan algunos resultados representativos.

ABSTRACT

A program of speckle observations at Lowell Observatory's Discovery Channel Telescope (DCT) and the Gemini North and South Telescopes will be described. It has featured the Differential Speckle Survey Instrument (DSSI), built at Southern Connecticut State University in 2008. DSSI is a dual-port system that records speckle images in two colors simultaneously and produces diffraction limited images to $V \sim 16.5$ mag at Gemini and $V \sim 14.5$ mag at the DCT. Of the several science projects that are being pursued at these telescopes, three will be highlighted here. The first is high-resolution follow-up observations for *Kepler* and *K2* exoplanet missions, the second is a study of metal-poor spectroscopic binaries in an attempt to resolve these systems and determine their visual orbits *en route* to making mass determinations, and the third is a systematic survey of nearby late-type dwarfs, where the multiplicity fraction will be directly measured and compared to that of G dwarfs. The current status of these projects is discussed and some representative results are given.

Key Words: binaries: visual — techniques: interferometric — techniques: high angular resolution — techniques: photometric

1. INTRODUCTION

Speckle imaging has been used in the study of binary stars since its inception in the 1970's. The ability of the technique to obtain high-resolution information and place astrometric measurements in the diffraction-limited regime at large telescopes permitted relatively short-period binaries to be successfully observed and measured with an imaging method. There were more systems that could be studied both spectroscopically and astrometrically, which led to more reliable stellar mass estimates. This continues to be an important use of the technique.

In the current environment where many large telescopes have adaptive optics systems and there are large long-baseline optical interferometers in operation that provide ultra-high resolution imaging information, speckle imaging has survived, and is even in a period of resurgence at present. In the context of these other techniques, speckle may be viewed as "single-aperture" interferometry, where the image products made from the raw speckle data frames take advantage of the fact that pairs of sub-apertures within the aperture of a large telescope generate fringe patterns that interfere on the image plane. Key to the reemergence of speckle imaging has been the advent of electron-multiplying CCD cameras (EMCCDs), a technology that amplifies the photoelectrons collected prior to readout, thereby lowering the effective read noise of a CCD chip. These

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devices are a near-perfect match of the requirements of speckle imaging: they are photon counters that have extremely high quantum efficiency.

There are several speckle observers who have moved to EMCCD-based speckle observing, including Docobo and Balega and their collaborators (*e.g.* Docobo *et al.* 2010), Tokovinin *et al.* (2016) and references therein, and our own efforts. The range of science programs being enabled by speckle imaging includes searching for stellar companions to stars that host exoplanets, systematic surveys of nearby stars to better understand binary statistics as a function of spectral type, and a renewed interest in the speckle imaging of asteroids and other extended objects. This paper will focus mainly on brief progress reports for three projects being pursued by the authors and their collaborators using the Differential Speckle Survey Instrument (DSSI), a dual-channel speckle camera built at Southern Connecticut State University in 2008.

2. OBSERVING WITH DSSI

Since its completion in 2008, DSSI has been been used at four telescopes: The WIYN 3.5-m telescope at Kitt Peak, the Discovery Channel 4.3-m Telescope at Lowell Observatory, and the Gemini-N and Gemini-S 8.1-m telescopes. In the case of WIYN observations, time was awarded both through time allocation committees at the consortium members (Yale and the University of Wisconsin), as well as occasionally through individual investigators applying through the normal NOAO Time Allocation Committee. In the case of Gemini, the instrument has enjoyed a formal visitor instrument status since 2012, where time has been advertised to the astronomical community and awarded on a competitive basis. At Lowell Observatory, the instrument has been made available to astronomers and adjuncts at Lowell, and some further time has been awarded to astronomers at consortium member institutions of the DCT.

Observing with DSSI entails taking many short-exposure frames of data. As DSSI has two EMCCDs, these can collect speckle frames in two colors simultaneously. One significant advantage of this is that separations below the diffraction limit can be measured by comparing the information gained at both wavelengths, as detailed in Horch *et al.* (2011). Light in a collimated beam is split by a dichroic filter, reflecting light with wavelength above a certain value while transmitting the light with wavelengths below this value. Bandpass filters are then mounted just after the dichroic in the collimated beam to give good speckle contrast. The instrument was designed for a

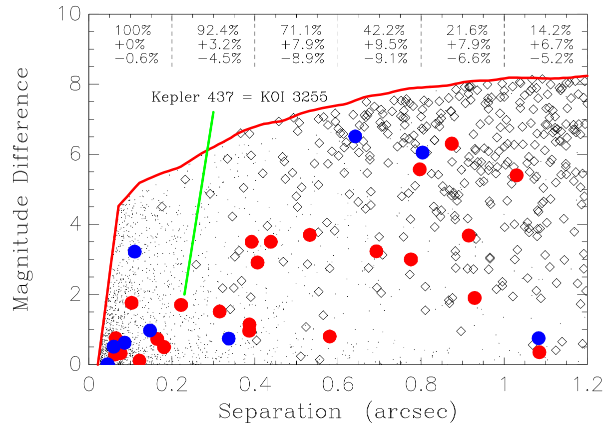

Fig. 1. Magnitude difference versus separation for companion stars to exoplanet candidate host stars discovered at Gemini with DSSI. The 2013 and 2014 DSSI runs are shown as red and blue filled circles. Dots represent the expected locations of bound companions given a Raghaven *et al.* (2010) distribution of companions, and diamonds give the expected locations of line-of-sight companions. The red curve marks the 5-σ detection limit with DSSI. We highlight Kepler 437 here as it hosts an earthlike planet.

survey mode, where many objects would be observed throughout the night in the same filter, so it does not have filter wheels. Mounting other filters and different dichroics is possible, but requires opening the instrument.

3. KEPLER AND K2 FOLLOW-UP

DSSI has been a workhorse instrument for *Kepler* and now *K2* ground-based follow-up observations. Some of the most significant results that have utilized DSSI data to assess the presence of stellar companions of exoplanet host stars include Crossfield *et al.* (2016), Howell *et al.* (2016), Hirsch *et al.* (2016), Furlan *et al.* (2016), Teske *et al.* (2015), and Everett *et al.* (2015), Ciardi *et al.* (2015) and Horch *et al.* (2014). Taken together, these papers show that binarity among exoplanet host stars is relatively common, comparable to the general field population of stars, at least for separations to which DSSI is sensitive at Gemini. In Figure 1, we plot some representative companions discovered at Gemini together with simulation results for bound versus line-of-sight companions in the direction of the *Kepler* field. Based on placement in the diagram, it is likely that the majority of companions discovered by speckle at Gemini are in fact gravitationally bound, and indeed some systems are confirmed to be bound from other analyses in the references above.

4. METAL-POOR SPECTROSCOPIC BINARIES

In order to study the effect of metallicity on the stellar mass-luminosity relation, we have identified and observed a number of nearby spectroscopic binaries with known metallicity. With the spectroscopic orbit in hand, then we can determine a visual orbit with relatively few data points, still obtaining very good mass estimates of the components. First results of our observing efforts were presented in Horch *et al.* (2015), where we found that the trend expected from the theory appears to hold, albeit with some uncertainty. Since that time, we have sought to obtain further observations of the sample to get better orbital elements and to add a few new targets. We are currently analyzing the data taken since 2015 and anticipate completing our analysis of orbit refinements and masses soon.

Figure 2 shows the separation regime that we can study with the stars in the sample as a function of metallicity. As expected, the more metal poor systems are somewhat more distant, and therefore the physical separation at the diffraction limit is larger, but in general, we can resolve components down to a couple of AU, which allows us to successfully provide astrometry for these systems. It is interesting to note that three systems we have observed, shown with an asterisk next to the data point, have a faint third companion that was not previously known. The most metal poor of these, YSC 128, was a system we have been observing for some time at the WIYN telescope with DSSI, so we have the opportunity to use this system to anchor the low-metallicity end of our study.

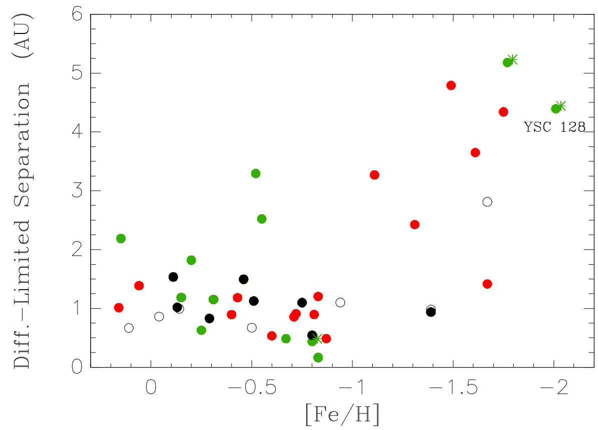

Fig. 2. A plot of the diffraction-limited separation achievable at Gemini with DSSI (in AU) for the metal-poor sample as a function of iron abundance. Hipparcos distances have been used. Filled circles are the eight systems that appear in Horch *et al.* (2015), open circles are summer systems we have observed since that time, green circles are the systems that form the winter observing list at Gemini-N, and red points are the Southern sample. YSC 128, the system described in the text, is shown at the upper right.

5. NEARBY K- AND M-DWARF SURVEYS

While the companion star fraction of field G-dwarfs has been well-established, but it has been shown by Winters *et al.* (2015) that the result for M-dwarfs is significantly lower than that for the field G-dwarfs. However, the multiplicity of these samples is still being studied, and speckle imaging can help make a survey of companions in the sub-arcsecond range more complete. As of this writing, we have nearly completed a survey of 1000 K dwarfs with 50 pc of the Sun, and dozens of new companions have so far been found. We are now working our way through a comparably large list of M dwarfs with DSSI, in collaboration with Winters and others. Further information about these surveys can be found in Nusdeo *et al.* (2017) and van Belle & Horch (2017).

6. LOOKING TOWARD THE FUTURE

One of us (S.H.) secured funding in 2015 to build two new speckle cameras that would continue the work started with DSSI primarily on exoplanet-related science. The first of these instruments, the NASA Exoplanet Star and Speckle Imager (NESSI) was commissioned in October of 2016 at the WIYN telescope and has effectively replaced DSSI there. A second instrument, named Alopeke, is slated to be commissioned at Gemini-N in October of 2017. A description of both instruments and their capabilities can be found in Scott *et al.* (2016). A key difference between DSSI and both new cameras is that the new cameras will have a "wide-field" mode, allowing users to image a 1 × 1-arcminute field with speckle frame rates. These images will undersample individual speckles in a stellar image, but nonetheless provides a detection system for high-speed imaging and photometry in addition to a standard, high-magnification speckle mode.

The dual channel nature of DSSI suggests that instead of taking science data in both channels, it would be possible with a slight reconfiguration to take science data in one channel and wavefront sensor data in the second channel. Löbb (2016) has studied this situation with simulated Gemini DSSI data, assuming that the instrument is fitted with a Shack-Hartmann wavefront sensor and local slopes of

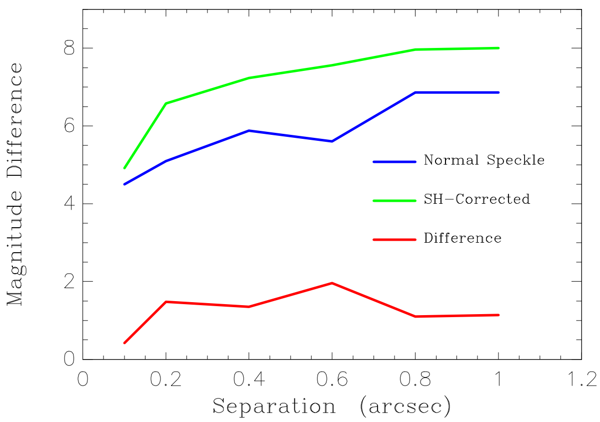

Fig. 3. Simulation results for utilizing Shack-Hartmann wavefront sensor data in combination with speckle data to improve sensitivity limits. The blue curve is the detection limit derived from standard speckle reduction, comparable to the real data in Figure 1. The green curve is the result of incorporating wavefront sensor information in the speckle analysis using the method of Löbb (2016). The red curve shows the increase in sensitivity obtained.

the wavefront were available from the second channel of the instrument. The result is that in analyzing the simulated speckle data using the normal reduction techniques, a sensitivity curve similar to the one shown for real Gemini DSSI data is obtained, but if the wavefront slopes are used to "flatten" the derived wavefront of the science data in software, then the sensitivity curve moves upward to larger magnitude differences, shown in Figure 3. This is potentially significant for faint companion detection with speckle imaging; one of us (G. vB.) is currently designing a two-channel camera where one channel is the wavefront sensor, and one channel has four separate wavelength speckle images multiplexed onto it.

Gaia will provide distance measures of exquisite precision for the stars in the surveys described above. It will also provide some relative astrometry of components, but given the orbital periods of many binaries and the expected lifetime of the *Gaia* satellite, most systems will need further observations to determine the orbital parameters of the system. DSSI is an instrument that is superior to *Gaia* in terms of resolution and in sensitivity to large magnitude differences. However, *Gaia* parallaxes for the projects presented can be combined with DSSI astrometry and relative orbits to determine stellar masses. There is much to be learned from combining the best distance information for these samples with sustained DSSI observing to obtain high-quality masses and relate them to other stellar parameters.

7. SUMMARY

We have briefly described the current use of the DSSI speckle camera at the Discovery Channel Telescope and the Gemini Observatory. The work has three main scientific aims: (1) to aid in *Kepler* and *K2* ground-based vetting of exoplanet candidate host stars, (2) to provide high-quality orbits and masses of metal-poor stars to enhance our understanding of the mass-luminosity relation of main-sequence stars, and (3) to assess the rate of companions for K- and M-dwarfs.

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