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Searching for Planetary Companions to Ultracool Dwarfs: Planet Hunting in the Near Infrared

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Abstract. Owing to their small masses and radii, Ultracool Dwarfs (UCDs; late-M, L, and T dwarfs) may be excellent targets for planet searches and may afford astronomers the opportunity to detect terrestrial planets in the habitable zone. The precise measurements necessary to detect extrasolar planets orbiting UCDs represent a major challenge. We describe two efforts to obtain precise measurements of UCDs in the Near Infrared (NIR). The first involves the robotic NIR observatory PAIRITEL and efforts to obtain photometric precision sufficient for the detection of terrestrial planets transiting UCDs. The second effort involves precise radial velocity measurements of UCDs in the NIR and a survey undertaken with the NIRSPEC spectrograph on Keck.

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1. Introduction

Today there are more than 2000 Ultracool Dwarfs (UCDs) known. These objects, many discovered with the 2-Micron All Sky Survey (2MASS, Skrutskie *et al.* 2006, Cruz *et al.* 2003) and the Sloan Digitl Sky Survey (SDSS, Hawley *et al.* 2002), are a well-studied class spanning the M, L, and T spectral types. Relatively little is known about the existence of planets around UCDs. The theoretical expectation from simulations of planet formation via core accretion is that it is possible to form terrestrial ($M < 5M_\oplus$) planets around UCDs (Payne & Lodato 2007). Observations of disks around UCDs in star-forming regions indicate that the fraction of these objects with protoplanetary disks is comparable to the fraction of solar-mass stars with disks (Luhman *et al.* 2005). Currently, searches for extrasolar planets rarely include any UCDs. Radial velocity surveys do include some targets of early-M spectral type (earlier than M5) and there is evidence from these surveys that “hot-Jupiter” companions to the early M dwarfs are relatively rare (i.e. Johnson *et al.* 2007). There are few observational constraints on the rate of occurrence of planetary companions of any mass to UCDs.

With their small masses, and correspondingly small radii, the photometric and spectroscopic signatures of a planetary companion of a given size and orbit around a UCD are large compared to the signals from the same planet orbiting a sun-like star. If precise measurements, comparable to those made today of sun-like stars, can be made for UCDs it becomes possible, in principle, to detect terrestrial planets orbiting these stars. At the same time, the low luminosities of the UCDs means that short-period terrestrial companions could potentially be located in the “Habitable Zone” where equilibrium temperatures are thought to be conducive to life.

The low effective temperatures, and very red colors, of the UCDs motivates observations in the near infrared (NIR) where the UCDs are much brighter than in the optical. The precise NIR measurements, both photometric and spectroscopic, required to detect planetary companions pose a significant observational challenge. We are working to develop techniques that will hopefully enable the detection of terrestrial companions to UCDs through both the transit and the radial velocity methods.

2. The Peters Automated InfraRed Imaging TELescope

Over a wide range of masses and ages UCDs are approximately the same size as Jupiter (Burrows *et al.* 2001). Transits by terrestrial planets described by the models of Valencia *et al.* (2005) will produce detectable flux decrements ΔF

$$\frac{\Delta F}{F} \approx 0.008 \left(\frac{M_p}{M_\oplus}\right)^{0.54} \tag{2.1}$$

where M_p is the mass of the planet. A transit by an Earth-mass planet results in an event with a depth of $\approx$ 8 mmag and a transit by a $10M_\oplus$ planet results in a transit depth of $\approx$ 0.03 mag. If photometry with sufficient precision can be produced, it becomes possible, in principle, to detect Earth-size planets with a targeted transit search.

We used the Peters Automated InfraRed Imaging TELescope (PAIRITEL) to observe a sample of UCDs over an extended period of time in order to evaluate the feasibility of a search for terrestrial planets transiting UCDs. PAIRITEL is a fully robotic 1.2 m NIR observatory at the F. L. Whipple Observatory, located on Mt. Hopkins, Arizona. We observed a sample of 13 UCDs over a period of 10 months in order to evaluate the quality of the resulting NIR photometry. Example light curves from three of the targets are shown in Figure 1. PAIRITEL has gathered more than 10^6 s of observations of UCDs (Blake *et al.* 2008b). The scarcity of bright UCDs makes it necessary for us to observe a single object at a time. This observing strategy is very different from most transit searches, which simultaneously monitor thousands of stars over a wide field of view. The possibility of short orbital periods ($P < 1$ day) and a relatively high percentage of time in transit make a targeted transit search for planets orbiting UCDs viable.

In addition to the orbital phase coverage, a important limiting factor in this transit search is the photometric precision that is achieved. We have considered many systematic effects in NIR differential photometry in order to achieve 0.01 mag precision. We carried out a simulation of planet detection efficiency using the PAIRITEL data. The results of this simulation are shown in Figure 1. We find that an extended campaign to monitor UCDs over a period of several years could provide significant sensitivity to Super-Earth planets orbiting close to the habitable zones of their hosts. In particular, a campaign using a network of telescopes distributed in longitude, allowing near complete phase coverage, could provide significant sensitivity to planets with periods less than one day and orbital separations $a < 0.005$ AU.

3. Radial Velocities in the NIR

Detecting and characterizing planetary companions to UCDs will require the development of new techniques for measuring precise radial velocities (RVs) in the NIR. The CO bandhead near 2.2 μm provides an excellent set of spectral features for RV measurements. This region is also rich in narrow CH_4 absorption features due to Earth's atmosphere, which we use as a wavelength reference. Starting from a set of high-resolution synthetic UCD spectra and a spectrum of Earth's atmosphere, we forward model the observed NIR spectra of UCDs in order to measure RV and the projected rotation velocity, $V \sin i$. A an example of the spectral modeling process is shown in Figure 2.

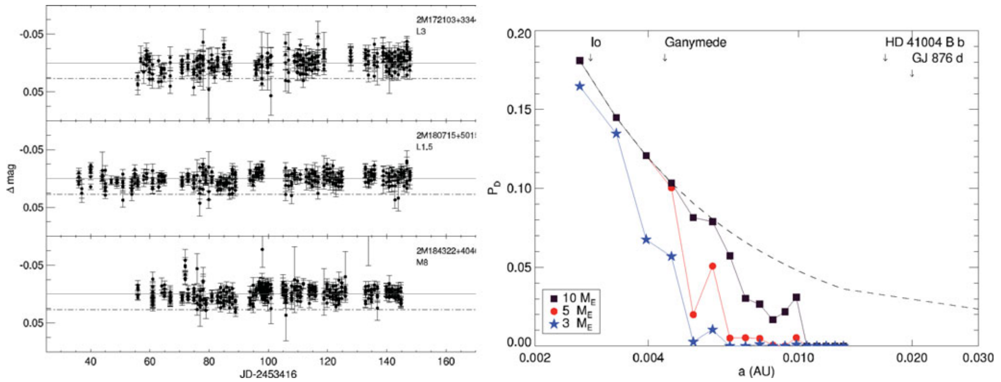

Figure 1. *Left*: Examples of three PAIRITEL light curves. Each point corresponds to the average of a set of simultaneous 180s J,H,K_s observation of the target. The dashed line corresponds to the depth of a transit by a $10M_\oplus$ companion. The spectral types of the three targets are also given. *Right*: Results of the simulation of planet detection efficiency using hypothetical PAIRITEL data from an intensive campaign to observe a target for 130 hours over three months. The dashed line is the geometric expectation based on the radii of the planet and UCD, $(R_{UCD} + R_P)/a$. The orbital separations of two moons of Jupiter, Io and Ganymede, as well as two known extrasolar planets, are shown. The orbits considered in the simulations extend from the Roche limit at ≈ 0.003 AU. The radius of Jupiter is $R_{\rm J}$=0.0004 AU, so the distance between a UCD and a planet orbiting at the Roche limit is still several times the radius of the UCD.

We have used Phoenix on Gemini-S and NIRSPEC on Keck to monitor about 75 L dwarfs over a period of four years (Blake et al. 2007, Blake *et al.* 2008a). The current RV precision is about 200 m s^{-1}, but simulations indicate that improvements to the analysis should result in a precision of 50 m s^{-1} from the extant spectra. We are currently sensitive to “hot-Jupiter” companions to UCDs as well as companions at longer orbital periods. The semi-amplitude of the RV signal due to a planetary companion orbiting a star is

$$K \approx 654 \text{ m s}^{-1} \left(\frac{P}{3\text{d}}\right)^{-1/3} \left(\frac{M_{\rm p}}{M_{\rm J}}\right) \left(\frac{M_{UCD}}{0.1M_\odot}\right)^{-2/3} \left(1-e^2\right)^{1/2} \sin i \tag{3.1}$$

where $M_{\rm J}$ is the mass of Jupiter, M_{UCD} is the mass of the UCD, e is the eccentricity of the planetary orbit, i is the inclination of the orbit to the plane of the sky, and P is the orbital period of the planet. With a precision of 50 m s^{-1} we are sensitive to companions with $M_p > 0.2M_{\rm J}$ and $P < 3$ days as well as more massive companions with $M_p > 1M_{\rm J}$ and $P < 200$ days.

These observations also provide a wealth of information about the physical properties of UCDs. The space velocities of the UCDs with parallax and proper motion measurements can constrain the age of the UCD population. Measurements of $V \sin i$ can be compared to models of UCD rotation as well as photometric observations with PAIRITEL. Our survey is also very sensitive to spectroscopic binaries, which can be used to constrain both the fundamental physical properties of UCDs (Blake 2008b) and the statistical properties of UCD binarity. An example of the NIRSPEC RV measurements of the M/L single-lined spectroscopic binary 2M0320−04 is shown in Figure 2. With a period of $P = 246.73 \pm 0.49$ days and an RV semi-amplitude of $K = 7.02 \pm 0.12$ km s^{-1} (Blake *et al.* 2008) this system is readily detectable through our Keck/NIRSPEC survey.

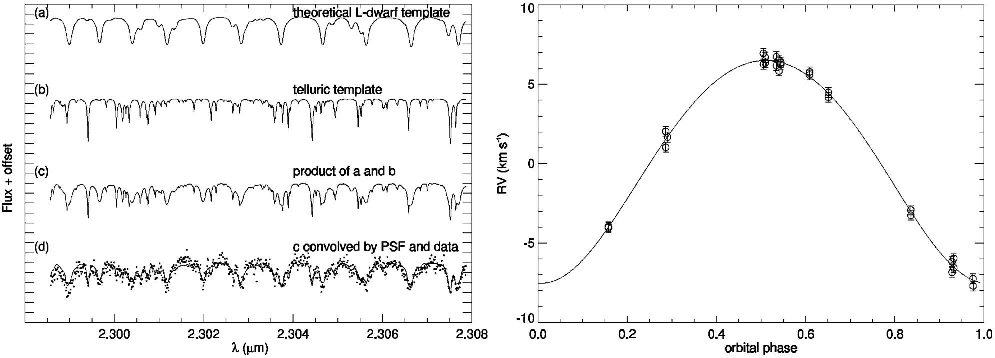

Figure 2. *Left*: Illustrative example of the steps in the NIR spectral modeling process: (a) is the rotationally broadened L dwarf theoretical spectrum, (b) is the observed KPNO telluric spectrum (c) is the product of (a) and (b), and (d) is the spectrum (c) convolved with the PSF. The data (small points) in spectrum (d) are the observed spectrum from our Phoenix observations of L dwarf 2M1155-37. *Right*: Keck/NIRSPEC measurements of the M/L single-lined spectroscopic binary 2M0320−04 phased to the orbital period of $P = 246.73$ days. The observations of this object span more than three years.

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