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A Keck/HST Survey for Companions to Low-Luminosity Dwarfs

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Abstract. We present preliminary results of an imaging survey for companions to low-luminosity dwarfs with spectral types ranging from M7 to L9. A K-band study with the Near Infrared Camera (NIRC) at the Keck telescope discriminates against background sources by searching for common proper motion. A complimentary HST/WFPC2 snapshot survey is better able to resolve close companions, but is not as sensitive at wide separations. Preliminary results from the Keck/NIRC survey have yielded the detection of 3 binaries in a sample of 10 L dwarfs, including one previously identified in HST imaging (Martín et al. 1999). All three have equal-component luminosities and physical separations between 5 and 10 AU. This result leads us to speculate that binary companions to L dwarfs are common, that similar-mass systems predominate, and that their distribution peaks at radial distances in accord both with M dwarf binaries and with the radial location of Jovian planets in our own solar system. To fully establish these conjectures, however, will require quantitative analysis of an appropriate sample. To this end, we outline a Bayesian scheme to test models of the underlying companion distribution with our completed imaging survey.

1. Introduction

Recent detections of planetary and brown dwarf companions to nearby stars have fueled efforts to undertake a complete inventory of circumstellar bodies (Mayor & Queloz 1995; Nakajima et al. 1995; Marcy & Butler 1996). It is thus likely that we stand at the beginning of an exciting era of astronomical discovery in which a gradually unfolding census promises to provide key evidence for the modes of origin for planets and binary stars. As part of this endeavor, we have undertaken a search for companions to recently discovered low-luminosity field dwarfs (Kirkpatrick et al. 1999; 2000). Our study will provide a first look at the binary companion rate for sub-stellar objects. Furthermore, it will yield a special opportunity for imaging giant Jovian planets, since sensitivity is enhanced in the reduced glare of faint dwarf primaries.

The local field detection rate of very low-luminosity dwarfs in infrared sky surveys suggests they comprise a sizeable population which is well represented by an extension of the field-star mass function, $\Psi(M) \propto M^{-\alpha}$, with $1 < \alpha < 2$ (Reid et al. 1999). The occurrence frequency of multiplicity among these systems is completely unknown; it is an open question as to whether the distribution of their companions matches that of M dwarfs or bears the stamp of a different, sub-stellar formation mechanism. Stellar companions are detected in approximately 35% of M dwarf systems with a distribution peaking at a radius in the range $3-30$ AU (Fischer & Marcy 1992; Henry & McCarthy 1993; Reid & Gizis 1997). Efforts to uncover the mass and radial distribution of extra-solar planets around M stars are just beginning to meet with success and have revealed super Jovian-mass planets within a few AU of their central stars, consistent with results for earlier spectral types (Marcy et al. 1998). The relationship of this population to that of binary companions and planetary systems like our own is a topic of current debate (Black 1997). The true answer will not be readily apparent until a more complete range of mass and orbital distances has been surveyed.

To date, very few multiple systems have been identified with L-dwarf components. Several L-dwarf secondaries have been discovered around nearby stars (Becklin & Zuckerman 1988; Rebolo et al. 1998; Kirkpatrick et al. 2000). Among a handful of known binary brown-dwarf systems (e.g., Basri & Martín 1997), only two have primary spectral types as late as L: 2MASSW J0345 is a double-lined spectroscopic L dwarf system (Reid et al. 1999), and DENIS-P J1228 was shown to be double in HST imaging observations (Martín et al. 1999). The latter is composed of equal-luminosity components with a projected separation of $0.275''$ (5 AU at the 18 pc distance of DENIS-P J1228). Here we report preliminary results from a Keck near-infrared imaging survey of a large sample of low-luminosity dwarfs and outline a complementary study with Hubble Space Telescope.

2. Survey Characteristics

2.1. Keck/NIRC Imaging Survey

Our target sample is culled from the 2MASS and DENIS near-infrared sky surveys and consists of objects spectroscopically confirmed to be L dwarfs together with a smaller sample of nearby very late M dwarfs. Survey parameters are plotted in Fig. 1, including sky coverage, spectral type, and range of distances. Imaging is carried out at the Keck I telescope with NIRC, a cryogenically-cooled near-infrared camera which incorporates a 256×256 Indium-antimonide array at the f/25 focus in an optical framework which yields a $0.15''$ plate scale and $38''$-square field of view (Matthews & Soifer 1994). The survey is sensitive to

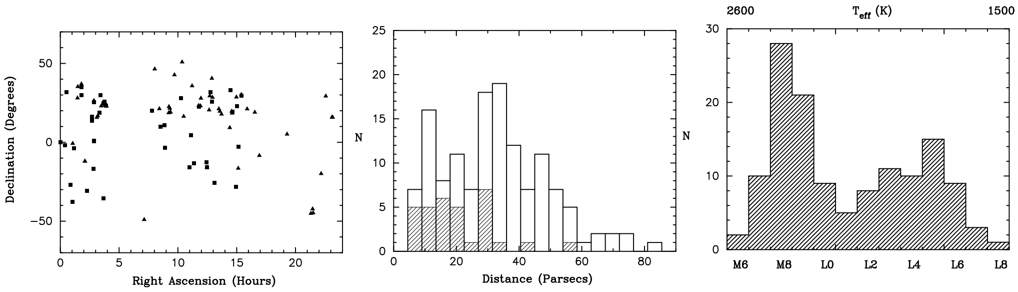

Figure 1. **Left)** Sky coverage for Keck/NIRC survey of low-luminosity dwarfs. Sample is culled from optical and near-infrared photometric surveys in sky regions avoiding the galactic plane. L dwarfs were identified with follow-up spectroscopy. **Center)** Range of distances for objects in survey. Hatched bars represent those objects for which distance has been determined by trigonometric parallax. **Right)** Distribution of spectral types in the survey. The bi-modal distribution is largely the product of search techniques; the L dwarf sample was identified from 2MASS and DENIS data.

companions brighter than $m_{\rm K} = 21$ at separations greater than $1''$ (5-50 AU in the sampled range of distances) within a $20'' \times 20''$ square aperture (out to 100-1000 AU), and is capable of detecting components with luminosity close to that of the primary ($m_{\rm K} \sim 13$) at $\sim 0.3''$ separation. At this level of sensitivity, several additional sources are detected in a typical frame. Repeat observations in a second epoch, one year or more later, are being taken to determine if any of these share a common proper motion with the target; second-epoch observations are complete for only a subset of the sample which includes 10 L dwarfs at present.

In addition to the common proper motion analysis of faint sources, we inspect the core of each of the primaries to search for extended emission associated with a marginally resolved binary. Second-epoch observations are used to obtain evidence of common proper motion and to mitigate systematic psf-distortion effects due to errors in phasing of the segmented primary mirror. Point-like sources observed nearby in the sky and within an hour of the target observations serve as psf measurements. Dithered images of candidate binaries and psf stars are not shifted and combined but are treated as independent data sets. Psf stars are fit in duplicate to each of the candidate binary images using a least-squares minimization method, to determine component properties.

2.2. HST/WFPC2 Imaging Survey

High contrast companions within $0.5''$ are better detected at spatial resolution that is not hampered by the effects of atmospheric seeing. We are carrying out a companion program with the Wide Field Planetary Camera 2 on HST to detect close companions to low-luminosity dwarfs. Equal-luminosity components are

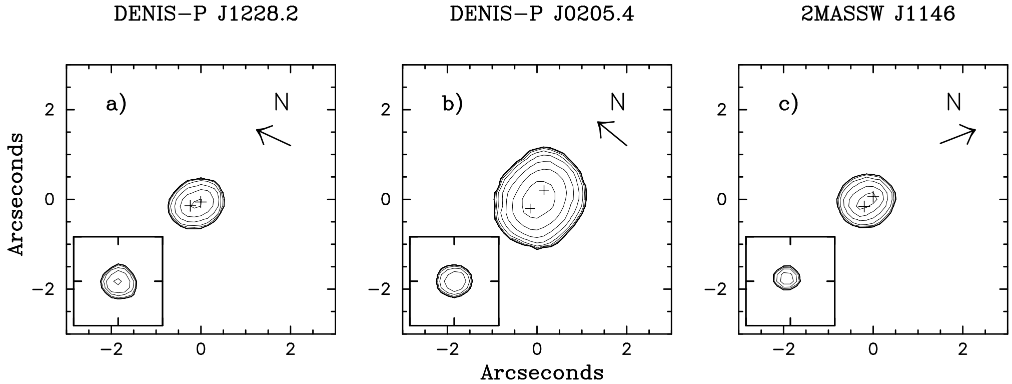

Figure 2. **a)** Contour plot taken from Koerner et al. (1999) of K-band imaging of DENIS-P J1228 together with that of Kelu-1, the "psf" star used to derive binary component parameters. Contours are at logarithmic intervals. Crosses mark the separation and PA of components derived in the psf fits to the data shown here. **b)** Plots as in a) for DENIS-P J0205 and associated psf star, LP 647-13, **c)** Plots as in a) and b) for 2MASSW J1146 and psf star 2MASSW J1145.

resolved at $0.09''$ and contrasting luminosities of δm = 5 (I band) are detectable outside $0.32''$ from the star.

3. Preliminary Results - Abundant L-Dwarf Binaries?

In preliminary analysis of Keck/NIRC image frames for which dual-epoch observations have been obtained, three objects met our criteria for reliable identification of a true close binary system (Koerner et al. 1999), including one imaged previously with HST/NICMOS by Martín et al. (1999). Contour plots of three L-dwarf binaries are displayed in Fig. 2, together with the psf stars used decompose them into separate components. In Fig. 3 are plotted the results of psf-fits to obtain the separation and PA for the components of DENIS-P J1228, DENIS-P J0205, and 2MASSW J1146. Mean values are $0.27\pm0.03''$, $0.51\pm0.03''$, $0.29\pm0.06''$ and $33\pm15°$, $92\pm18°$, $206\pm19°$, respectively. Projected separations correspond to physical separations of 4.9, 9.2, and 7.6 AU at distances implied by obtained trigonometric parallaxes (Dahn et al. 2000). Flux-component ratios for the binaries are 1.1 ± 0.4, 1.0 ± 0.4, and 1.0 ± 0.3, respectively.

The binary systems presented here have similar projected separations (5 to 9 AU) and luminosity ratios near unity. They represent the first binary detections in preliminary analysis of a larger dual-epoch survey in which only 10 L-dwarf images have been completely analyzed in two epochs. No companions with wider separations or more highly contrasting luminosities were found thus far. These preliminary results suggest a conjecture for further testing: namely, that multiple systems are common in the L dwarf population, that their distribution peaks at radial separations like that of both Jovian planets in our solar system and M dwarfs generally ($\sim 5-30$ AU), and that low-contrast mass ratios

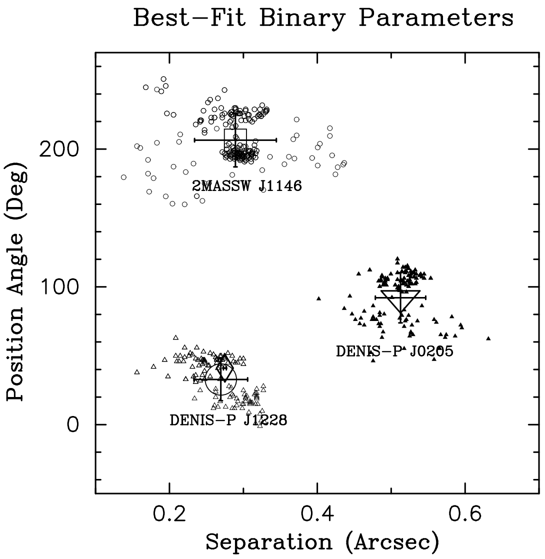

Figure 3. Binary separation and position angle from psf-fits of individual frames for 2MASSW J1146 (small open circles), DENIS-P J1228 (small open triangles), and DENIS-P J0205 (small filled triangles). The mean of each of the measurements is plotted as a large open symbol for each object with error bars that mark the rms deviation about the mean. The HST/NICMOS result for DENIS-P J1228 is plotted as an open diamond (from Koerner et al. 1999).

are common. The latter claim is especially in need of testing, since our survey is not very sensitive to companions at the separations reported here if they have high luminosity contrast ratios. Further, the magnitude-limited surveys from which our sample is taken are biased toward the detection of equal-luminosity binaries, since their combined luminosity is greater than for single stars of the same spectral type. Ultimately, techniques with both high resolution and high dynamic range must be applied to a larger sample to reliably identify the distribution of circumstellar bodies that encircles this population of very cool objects.

4. Bayesian Inference of the Underlying Companion Distribution

We would like especially to discover the probability distribution of stellar and planetary companions in order to constrain theories of their origin; a successful theory should account for that distribution. In addition, an intensely human interest drives us to seek to understand how many habitable circumstellar environments exist and how typical is the planet on which we find ourselves. It will be decades at least before the inventory of circumstellar objects is complete enough to rely on counting statistics alone to provide the whole answer. In the interim, some regions of parameter space for model probability distributions will be more completely sampled than others. Relatively luminous companions at distances of 100 AU will soon be largely accounted for in nearly all stars detected nearby, for example. As parts of this census come to light, it will be challenging to ascertain the reliability of distribution estimates for substellar companions that are based on counting in incomplete samples.

Strictly speaking, the sampling of the companion distribution in our completed and combined Keck and HST surveys will still be incomplete, since high-luminosity-contrast companions close to the star or wide companions separated by more than 20" could go undetected. Furthermore, the range of linear separations is inhomogeneously sampled, since a wide range of distances is represented by the source list. Rather than simply count the number of detections and correct for incompleteness, we prefer to use a Bayesian model-fitting approach to quantify how well model companion distributions are constrained by our data. As outlined below, this approach yields the relative probability of a model distribution, given the data. By calculating this for a suitable range of models, we can determine both the most likely model, and the degree to which this choice is mandated by the data.

According to Bayes Theorem, the probability of a model given the data, $P < M|D >$, is calculated by multiplying the probability of the data given the model, $P < D|M >$, times the *a priori* probability of the model, $P < M >$. For the case of a model distribution that is a function only of linear separation, $R = \theta/\pi$ with angular separation θ and trigonometric parallax π, and luminosity L, the calculation of $M(R, L)$ is straightforward for an individual image frame D_i. The probability of a null detection is simply one minus the probability of a detection. Since the model is, *itself,* the probability of a detection, we can calculate this by integrating over one minus $M(R, L)$ as simply

$$P < D_i|M > = \int_{R_{in}}^{R_{out}} \int_{L_{ul}}^{L_{prim}} (1 - M(R, L)) dRdL$$

where R_{in} and R_{out} define the inner and outer linear separations to which the image is sensitive, and L_{prim} and L_{ul} are, respectively, the luminosity of the primary and the upper-limit luminosity for the detection of a companion. Typically, $L_{ul} = L_{ul}(R)$ for small angular separations. For images where a companion is detected at separation R' with luminosity L', the probability of the result, given the data, is given by

$$P < D_i|M > = \int_{Rin}^{R_{out}} \int_{L_{ul}}^{L_{prim}} \delta(R', L') M(R, L) dRdL$$

where $\delta(R', L')$ is the Dirac delta function. These terms may then be multiplied by the prior probability of the model according to Bayes Theorem. In the absence of any previous notions about the distribution, a "flat prior" may used by simply setting $P < M > = 1$.

The probability of a particular model, given all the image frames, is then the normalized sum of the probabilities for the N individual frames:

$$P < M|D > = \frac{\sum P < M|D_i >}{N} \quad .$$

A wide range of models may be compared in this way by calculating the relative probability, $P_{rel} < M_j|D >$, for the j^{th} model and normalizing over the whole suite of models considered:

$$P_{rel} < M_j|D> = \frac{P < M_j|D>}{\sum P < M_i|D>} \quad .$$

This approach has the advantage of bringing to bear all the information inherent in an inhomogeneous data set and weighting proportionally its influence on the choice of the most probable models. If, for example, only a few images test the model in some range of linear separations, their contribution to the overall probability will be small, such that models which vary in their estimate of companions at those separations will not have widely contrasting probabilities. Conversely, constraints will be strong in regions of the model parameter space that are densely sampled by the data. By considering an appropriate range of models, confidence levels as a function of parameter values can be attached to the best-fit model.

5. Parametrizing the Model Distribution

The scientific usefulness of the above methodology will depend heavily on the choice of models considered. It is possible, of course, to aim only to fit some analytic function to the data so as to derive a best-fit simplified representation of the observations. This is done easily by simply fitting a model which is parametrized in the directly measurable quantities, angular separation and relative luminosity. But it would be more worthwhile to derive a distribution function with physically meaningful parameters that have theoretical significance. The underlying properties which describe binary systems most *completely* are the orbital elements and masses. But theories of origin may be constrained by a few of these or by derivative quantities, such as semi-major axes or angular momentum. We note, for example, that binary origin simulations show a marked dependence on β, the ratio of rotational to gravitational energy in the original cloud (cf. Bonnell & Bastien 1992).

The testing of underlying physical models can proceed as above, so long as an appropriate transformation exists between the physical quantity and what is observed. For example, the most probable value of the semi-major axis, $a_{\rm rel}$, for a companion with observed angular separation θ and system distance d has been estimated by Fischer & Marcy (1992) using Monte Carlo simulations to be

$$< a_{\rm rel} > = 1.26 d < \theta > \quad .$$

This transformation can be incorporated easily into a scheme to determine an underlying model distribution of companions which is a function of $< a_{\rm rel} >$ rather than θ. For main sequence stars, a transformation between luminosity and mass can be accomplished with relationships obtained by dynamic mass determinations (cf. Henry et al. 1999). For L dwarfs, the situation is not well-determined empirically but requires theoretical models which relate mass, age, and luminosity (e.g., Burrows et al. 1997). To obtain the coveted distribution of masses from these relations, assumptions about stellar ages will be required.

Further complications are introduced by the inclusion of higher-order multiple systems and, ultimately, in the consideration of planetary systems as well. The increased effort may well be worth the undertaking, since it may yield a general taxonomic classification of multiple dwarf and planetary systems with theoretical significance and descriptive power for characterizing the frequency and types of circumstellar systems. To this end, we will fit models in a variety of parametrized prescriptions. We thus consider the application of Bayesian inference to the problem of the low-luminosity dwarf companion frequency to comprise a pilot study for larger objectives.

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