DISCOVERY OF A WIDE LOW-MASS BINARY SYSTEM IN UPPER SCORPIUS

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Abstract

Using the near-infrared spectrometer SpeX and its slit-viewing camera at the IRTF, I have resolved a low-mass member of the Upper Scorpius OB association into a double star. From $K$-band images of the pair, DENIS-P J161833.2-251750.4 A and B, I measure a separation of $0''.96$ and a magnitude difference of $\Delta K = 0.42$. I present resolved 0.8-2.5 $\mu$m spectroscopy of the two objects, both of which exhibit signatures of youth in the shape of their $H$- and $K$-band continua, demonstrating that both are members of Upper Scorpius rather than field stars. In addition, through a comparison to optically-classified pre-main-sequence objects, I derive a spectral type near M5 for each component, corresponding to a mass of $\sim 0.15 M_\odot$ with the evolutionary models of Chabrier and Baraffe. The probability that this pair is composed of unrelated M-type members of Upper Scorpius is $\sim 10^{-5}$. When added to the recent discoveries of other wide, easily disrupted low-mass binaries, this new system further establishes that the formation of low-mass stars and brown dwarfs does not require ejection from multiple systems. These observations also indicate that wide low-mass binaries can form in star-forming environments as well as in smaller clusters where the previously known wide pairs have been found. Thus, the available data show no perceptible effect of star-forming environment on the prevalence of loosely bound low-mass systems.

Subject headings: infrared: stars — stars: evolution — stars: formation — stars: low-mass, brown dwarfs — binaries: visual — stars: pre-main sequence

1. INTRODUCTION

The multiplicity of stars is influenced by the specific characteristics of the star formation process, and thus has been the subject of extensive measurements. Similarly, in an attempt to gain insight into the formation of brown dwarfs, recent studies have heavily scrutinized the binary properties of objects near and below the hydrogen burning mass limit in the solar neighborhood [Koerner et al. 1999; Martin et al. 2000; Gizis et al. 2003; Reid et al. 2001; Close et al. 2002; Chauvin et al. 2004; Bouy et al. 2004; Burgasser et al. 2003; Freed et al. 2003; Siegler et al. 2003; Forveille et al. 2003; Liu & Leggett 2005; Gelino & Kulkarni 2005], as well as in small, open clusters (Martín et al. 1998, 2000, 2003), and young clusters and associations (Neuhäuser et al. 2002; Bouy et al. 2004; Chauvin et al. 2004, 2005; Luhman 2005; Luhman, McLeod, & Goldfinger 2005; Kraus, White, & Hillenbrand 2005). Most of the binary low-mass stars and brown dwarfs in these surveys exhibit maximum separations of $a \sim 20$ AU, which is consistent with the predictions of the embryo ejection scenario for the formation of low-mass bodies [Reipurth & Clarke 2001; Boss 2001; Bate et al. 2002]. However, a small but growing number of low-mass binaries have been found at wider projected separations that range from 33-41 AU [Harrington et al. 1974; Martin et al. 2000; Chauvin et al. 2004; Phan-Bao et al. 2005; Mamajek et al. 2005] to beyond 200 AU [Gizis et al. 2000; Luhman 2004; Billeres et al. 2005]. Because these wide binaries are weakly bound and extremely fragile, it is unlikely that they have been subjected to violent dynamical interactions, indicating that some low-mass stars and brown dwarfs are able to form without the involvement of ejection. In fact, the role of ejection may be minor based on other aspects of the multiplicity of low-mass objects [Maxted & Jeffries 2003].

To fully utilize multiplicity as a probe of the formation of low-mass bodies, it is necessary to consider populations spanning a range of ages and star-forming conditions. OB associations represent an area of this phase space that remained unexplored until Kraus, White, & Hillenbrand (2005) obtained HST images of low-mass members of Upper Scorpius, which has an age of 5 Myr [de Geus, de Zeeuw, & Lub 1989; Preibisch & Zinnecker 1999] and is the nearest OB association at a distance 145 pc [de Zeeuw et al. 1994]. Among their 12 targets, they discovered three binaries, all with projected separations less than 18 AU. Kraus, White, & Hillenbrand (2005) tentatively suggested that this absence of wide systems in Upper Sco relative to lower density clusters like Chamaeleon I and TW Hya [Chauvin et al. 2004; Luhman 2004] might indicate a variation in the formation process of low-mass binaries with star-forming environment.

In this Letter, I report the discovery of a widely-separated low-mass binary star in Upper Sco, which was found serendipitously during a spectroscopic survey of the low-mass members of this association. I present near-infrared (IR) images and spectroscopy of the components of the pair, measure their spectral types and assess their membership in a binary system, and discuss the implications of this new pair.
While conducting a spectroscopic survey of known low-mass members of the Upper Sco association on 2005 June 16 with SpeX (Rayner et al. 2003) at the NASA Infrared Telescope Facility (IRTF), I found that one of the targets, DENIS-P J161833.2-251750.4 (Martín, Delfosse, & Guieu 2004), appeared as a ~ 1″ double on the slit-viewing camera. To further investigate the nature of this pair, I performed the imaging and spectroscopy described in this section.

2.1. Photometry

To measure the flux ratio of the components of DENIS-P J161833.2-251750.4 (hereafter DENIS 1618-2517), I used the slit-viewing camera on SpeX. This camera contained a 512 × 512 Aladdin 2 InSb array and had a plate scale of 0″12 pixel⁻¹ (Rayner et al. 2003). Through a K filter, I obtained 18 dithered one-second exposures. These images were median combined to produce a flat field image, which was then divided into each original exposure. The 12 frames with the best image quality were registered and combined. A 5″ × 5″ subsection of the resulting image surrounding DENIS 1618-2517 is shown in Figure 1. The components of this pair exhibit FWHM= 0″5 in this image. I extracted photometry for each object with the task PHOT under the IRAF package APHOT using a radius of three pixels, arriving at a magnitude difference of ∆K = 0.42 ± 0.03 mag. To measure astrometry for the pair, I first determined the rotation between the cardinal directions and the array axes using the 2MASS coordinates of DENIS 1618-2517 and the one other 2MASS source appearing in the image (2MASS 16183428-2518067). With this information, I measured a position angle of 50.3 ± 1° for the secondary relative to the primary. Using the plate scale from Rayner et al. (2003), I then measured a separation of 0″96 ± 0″04 for the pair.

2.2. Spectroscopy

Spectra were obtained of the components of DENIS 1618-2517 using SpeX in the prism mode with a 0″5 slit. This configuration produced a wavelength coverage of 0.8-2.5 μm and a resolution of R ~ 200. After adjusting the position angle of the slit to align it with the axis connecting the pair, I selected an integration time of 30 sec and obtained a total of 18 exposures during a sequence of dithers between two positions on the slit. The 10 frames with the best image quality were reduced with the SpeXtool package (Cushing, Vacca, & Rayner 2004). The data were corrected for telluric absorption with the method described by Vacca et al. (2003).

3. ANALYSIS

3.1. Spectral Classification

I now use the photometry and spectroscopy from the previous section to examine the spectral types and extinctions of the components of DENIS 1618-2517. Martín, Delfosse, & Guieu (2004) found that the Hα emission and Na I absorption in an unresolved optical spectrum of the pair were indicative of youth and thus membership in Upper Sco. In the SpeX data, I find evidence of youth in both objects. As shown in Figure 2, each spectrum exhibits a triangular H-band continuum, which is a distinguishing characteristic of cool pre-main-sequence objects (Lucas et al. 2001). The depths of the optical and IR molecular absorption bands, primarily TiO, VO, and H2O, are also very similar between the two objects, demonstrating that the two objects have the same spectral type to within ~ 0.5 subclass. In comparison, two young low-mass stars at the same age with a K-band magnitude difference of 0.42 are predicted to have ∆T ~ 70 K (Baraffe et al. 1998) which corresponds to ~ 0.5 subclass (Luhman et al. 2003). Thus, the relative spectral types and magnitudes of the components of DENIS 1618-2517 are consistent with the coevality expected for a binary system.

Although the absorption band strengths agree between the two objects, the secondary is redder beyond 1.7 μm. This is difficult to explain as a difference in spectral type or extinction, and instead probably is due to excess emission from circumstellar material around the secondary, an imperfect separation of the light from the two objects during extraction of their spectra, or the combination of misalignment of the slit along the binary axis and differential refraction. Meanwhile, the IR spectra of both DENIS 1618-2517 A and B are significantly redder than most of the other low-mass members of Upper Sco that were observed during the same run. The same trend is present in the 2MASS J − H and H − Ks colors of these objects and is consistent with extinction. Relative to the bluest (i.e., unreddened) SpeX data of members of Upper Sco and other young clusters at M5-M6 (Luhman, McLeod, & Goldenson 2005), the spectrum of DENIS 1618-2517 A+B exhibits an extinction of AV ~ 3. The presence of significant reddening is additional evidence that these objects are not foreground field dwarfs. Based on the strength of the molecular absorption bands, DENIS 1618-2517 A and B are earlier than most of the other Upper Sco members observed in this run, which have optical spectral types that range from M5 to M9 (Ardila, Martín, & Basri 2004). This suggests that DENIS 1618-2517 A+B may be closer to M5 than the value of M6 measured by Martín, Delfosse, & Guieu (2004). I find the same result when I compare the pair to optically-classified members of other young clusters. For instance, as shown in Figure 2, the molecular absorption bands of DENIS 1618-2517 A+B agree better with those of MHO 6 than with MHO 5, which have optical types of M4.75 and M6, respectively (Briceno et al. 2002). The relatively large reddening toward DENIS 1618-2517 may have caused Martín, Delfosse, & Guieu (2004) to arrive at a spectral type that was slightly too late. Combining a spectral type of M5 with the temperature scale of Luhman et al. (2003) and the evolutionary models of Baraffe et al. (1998) implies a mass of ~ 0.15 M⊙ for each component of DENIS 1618-2517.

3.2. Evidence of Binarity

The results from the previous section and from Martín, Delfosse, & Guieu (2004) demonstrated that the components of DENIS 1618-2517 are young members of Upper Sco. I now examine if they are likely to comprise a true binary system rather than a pair of unrelated members of the association that happen to have a small pro-

2 The relatively high extinction toward DENIS 1618-2517 could be caused by local circumstellar dust or cirrus clouds in the general vicinity of DENIS 1618-2517 (Meyer, Wilking, & Zinnecker 1993).
jected separation. The surface density of M-type members of Upper Sco is ~ 5 deg^{-2} and the total area of the association is ~ 100 deg^2 [Ardila, Martín, & Basri 2000; Preibisch, Guenther, & Zinnecker 2001; Preibisch et al. 2002; Martín, Delfosse, & Guieu 2004]. Across the entire association, the probability of finding a pair of M-type members with a projected separation of a ≤ 1'' is 3 × 10^{-4}. The observations that discovered this pair considered only a small fraction of the membership (a few dozen) and were not designed to detect close pairs. As a result, the relevant probability for DENIS 1618-2517 is lower by at least an order of magnitude. Based on the very low value of this probability, I conclude that DENIS 1618-2517 A and B comprise a binary system rather than two unrelated members of Upper Sco. Using the average distance of 145 pc for the association [de Zeeuw et al. 1999], the projected separation of 0.96 of this pair corresponds to 140 AU.

Demonstrating a common proper motion for a pair of stars is the conventional method of conclusively establishing binarity in the solar neighborhood, but it is less useful for young populations because even unrelated cluster members are comoving at the level of precision typically available for these measurements. For instance, the common proper motions measurements for the recently discovered substellar companions to GQ Lup [Neuhäuser et al. 2003] and 2M 1207-3932 [Chauvin et al. 2003] are not precise enough to distinguish between true binaries and comoving unbound cluster members seen in projection near each other. Thus, for GQ Lup, 2M 1207-3932, previously known pairs in Upper Sco [Kraus, White, & Hillenbrand 2003], and indeed the vast majority of visual doubles in young clusters and associations, available evidence of binarity is based on the same statistical considerations presented in this work for DENIS 1618-2517. Only the value of the probability differs among these binaries, which depends on the separation of a given pair and the surface density of cluster members. The probability of unrelated clusters members with small separations is exceedingly low for sparse populations like Upper Sco, Chamaeleon, Lupus, and TW Hya [Kraus, White, & Hillenbrand 2003; Luhman 2004; Neuhäuser et al. 2003; Chauvin et al. 2004] but non-negligible for dense clusters like the Trapezium in Orion [Prosser et al. 1994].

4. DISCUSSION

As with the brown dwarf pair in Chamaeleon from Luhman (2004), the binarity of DENIS 1618-2517 was discovered serendipitously and thus cannot be used at this time in a multiplicity measurement for low-mass members of Upper Sco. However, the mere existence of this binary system has important implications. First, DENIS 1618-2517 is one of only a few known low-mass binaries with very wide separations (a > 100 AU, Gizis et al. 2000; Luhman 2004; Billères et al. 2003). These wide pairs are fragile and easily disrupted, and thus demonstrate that some low-mass stars and brown dwarfs can form without the assistance of ejection. In addition, with these observations of DENIS 1618-2517, wide low-mass binaries are now known across a wider range of star-forming conditions, from small, sparse clusters (Chamaeleon) and to rich OB associations (Upper Sco). Thus, in the measurements available to date, the formation of wide low-mass binaries has no discernible dependence on star-forming environment.

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REFERENCES


Wide Binary in Upper Scorpius 3
Fig. 1.— $K$-band $5'' \times 5''$ image of the binary system DENIS-P J161833.2-251750.4 obtained with the slit-viewing camera on SpeX (FWHM = 0.96'').

Fig. 2.— Near-IR spectrum of both components of DENIS 1618-2517 compared to spectra of Taurus members MHO 6 (top) and MHO 5 (middle). The latter sources have optical spectral types of M4.75 and M6 [Briceño et al. 2002] and have been reddened by $A_V = 2.2$ and 1.7 to match the overall slope of DENIS 1618-2517 A+B. The resolved spectra of A and B exhibit similar spectral types (bottom). The spectra are normalized at 1.68 $\mu$m.