INFRARED SPECTROSCOPY OF THE ULTRA–LOW-MASS Binary OPH 162225–240515

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Received 2006 September 11; accepted 2006 October 19; published 2006 November 16

ABSTRACT

Binary properties are an important diagnostic of the star and brown dwarf formation processes. While wide binaries appear to be rare in the substellar regime, recent observations have revealed Ophiuchus 162225–240515 (2MASS J16222521–2405139) as a likely young ultra–low–mass binary with an apparent separation of ∼240 AU. Here we present low-resolution near-infrared spectra of the pair from NTT/SOFI (R ≈ 600) and VLT/ISAAC (R ≈ 1400), covering the 1.0–2.5 μm spectral region. By comparing them to model atmospheres from Chabrier & Baraffe and Burrows et al., we confirm the surface temperatures to be $T_\text{eff} = 2350 \pm 150$ K and $T_\text{eff} = 2100 \pm 100$ K for the two components of the binary, consistent with earlier estimates from optical spectra. Using gravity-sensitive K1 features, we find the surface gravity to be significantly lower than field dwarfs of the same spectral type, providing the best evidence so far that these objects are indeed young. However, we find that models are not sufficiently reliable to infer accurate ages/masses from surface gravity. Instead, we derive masses of $M_\alpha = 13^{+8}_{-4} M_J$ and $M_\beta = 10^{+5}_{-4} M_J$ for the two objects using the well-constrained temperatures and assuming an age of 1–10 Myr, consistent with the full range of ages reported for the Oph region.

Subject headings: binaries: general — planetary systems — stars: individual (2MASS J16222521–2405139) — stars: low-mass, brown dwarfs — stars: pre–main-sequence

1. INTRODUCTION

Growing evidence suggests that the bottom end of the stellar initial mass function extends well into the giant planet regime (<15$M_J$). A few dozen free-floating brown dwarfs with inferred masses near or below the deuterium-burning limit have been identified in the σ Orionis association (Zapatero Osorio et al. 2000) and the Orion Nebula cluster (ONC; Lucas & Roche 2000). Some of them have been confirmed as cool objects that are likely young cluster members through follow-up spectroscopy (Martín et al. 2001; Barrado y Navascués et al. 2001; Lucas et al. 2001, 2006).

However, very little is known about the properties of these isolated planetary mass objects (IPMOs or “planemos”) because they are extremely faint at the distances of σ Ori and the ONC (∼350–450 pc), and only a couple more have been identified in closer star-forming regions (Testi et al. 2002; Luhman et al. 2005). Recently, by combining ground-based optical and near-infrared photometry with Spitzer-Legacy Survey data, Allers et al. (2006) identified six new candidate planemos in three nearby regions, at distances ≤150 pc. In addition, based on their infrared excess, these objects appear to be surrounded by circum-substellar disks, just like many of the higher mass young brown dwarfs (e.g., Jayawardhana et al. 2003). Based on optical spectra, Jayawardhana & Ivanov (2006b) confirmed four of the candidates as ultra–low–mass objects and a fifth as a somewhat higher mass brown dwarf; the sixth turned out to be a likely background source.

Jayawardhana & Ivanov (2006a) reported that one of the newly identified planemos, Oph 162225–240515 (hereafter Oph 1622), is in fact an ∼240 AU binary, based on optical and infrared images as well as optical spectra. Independently, Allers (2005) and later Close et al. (2006) also observed Oph 1622 to be binary. By comparison to late-type objects, Jayawardhana & Ivanov (2006a) derived spectral types of M9 and M9.5–L0, for the primary and the secondary, respectively. The authors made a strong case for the youth, coevality, and physical association of the two objects, based on several lines of evidence, and derived masses of $\sim 14 M_J$ and $(7–8) M_J$ for them in comparison to Baraffe et al. (2003) models.

The existence of an ultra–low–mass binary with a wide separation comes as somewhat of a surprise, given the paucity of wide binaries in the substellar regime (e.g., Bouy et al. 2003; Gizis et al. 2003; Kraus et al. 2006), and poses a challenge to the ejection model for brown dwarf formation (e.g., Bate et al. 2002). Given the importance of Oph 1622 as a benchmark binary, here we present follow-up infrared spectroscopy to derive independent additional constraints on the nature of this pair.

2. OBSERVATIONS

Spatially resolved, low-resolution (R ≈ 1400), near-infrared (NIR) spectra of Oph 1622 (2MASS J16222521–2405139) were obtained in service mode under excellent seeing (<0.76 in V) on 2006 July 06 in the J and K bands, and on 2006 July 19 in the H band. The NIR instrument ISAAC (Infrared Spectrometer And Array Camera) was used in spectroscopic mode, mounted on the 8.2 m Antu telescope, one of the Very Large Telescope (VLT) units located at Paranal, Chile, operated by the European Southern Observatory. A slit width of 0.3” was used, with a pixel scale of 0.147 pixels”1 on a 1024x pixel array. The spectral regions covered are 1.07–1.44, 1.42–1.89, and 1.84–2.56 μm, for J, H, and K, respectively. The slit was aligned with the binary, and the telescope nodded 15” along the slit direction between exposures. Exposure times were 8 × 120 s in J, 20 × 120 s in H, and 30 × 117 s in K. As...
telluric standards, the B stars HIP 84292 and HIP 84435 were observed on 2006 July 11 and 2006 July 19, respectively.

Additional lower resolution spectra ($R \sim 600$), covering 0.95–1.64 and 1.53–2.50 $\mu$m, were obtained under average seeing ($\sim 1.1$" in $V$) on 2006 August 10 with the SOFI (Son of ISAAC) instrument on the 3.58 m New Technology Telescope (NTT), located at La Silla, Chile, and operated by the European Southern Observatory. A 1" slit was used, with a pixel scale of 0.288 pixels $^{-1}$ on a 1024$^2$ pixel array. The slit was aligned with the binary, and the telescope nodded 25" along the slit direction between exposures. Exposure times were 2 $\times$ 120 s for both the blue and red grisms. The Sun-like G star HIP 84181 was observed as a telluric standard.

Reduction of the ISAAC and SOFI spectra proceeded in a similar fashion. The sky for every exposure was estimated by averaging over temporally close exposures, where the star was offset to a different position on the array. After sky subtraction, the frames were flat-fielded. The spectra were then extracted using an optimal extraction algorithm developed by M. H. van Kerkwijk (2006, private communication), that fits two Moffat functions (Moffat 1969) simultaneously to the binary. The $0.5$ and 1" resolutions of ISAAC and SOFI, and the low flux ratio ($\sim 2$) and large separation ($\sim 2$") between the components, ensure that contamination between the two extracted spectra is not an issue. Wavelength calibration was obtained by measuring telluric OH emission lines (Rousselot et al. 2000) found in abundance in the science frames. The procedure was repeated for the telluric standards. The science spectra were then flux-calibrated by multiplying by a model spectrum of the standard star (from Pickles 1998), resampled to the observed sampling, and dividing by the observed standard. No extinction correction was made to the spectra.

3. RESULTS AND DISCUSSION

The merged SOFI spectra are shown in Figure 1, and the ISAAC $J$, $H$, and $K$ spectra in Figures 2, 3, and 4, respectively. The (pseudo)equivalent width of several lines, measured in the ISAAC spectra, are reported in Table 1. The separation of the binary was measured from ISAAC spectra to be $1\farcs944 \pm 0\farcs010$, where the estimate includes uncertainties of the pixel scale (0.5%) and orientation of the slit (1°). This agrees well with previous measurements (Jayawardhana & Ivanov 2006a).

Because of the great diversity of near-infrared spectral shapes found among young low-mass objects (Lucas et al. 2001, 2006) and the lack of an extensive library of young late-type spectral
standards, it is difficult to constrain the spectral type from near-infrared spectra alone. The continuum is suppressed by a multitude of molecular bands, many of which are gravity-sensitive, and hence define a “pseudocontinuum” that depends on both temperature and gravity. Finding a unique temperature and gravity by comparing to model atmospheres is also problematic; despite great advancements of models in recent years, missing opacities limit their reliability on a detailed level (e.g., Allard et al. 2000). We compared the low-resolution SOFI spectra (Fig. 1) to DUSTY models by Chabrier et al. (2000) and to more recent models by Burrows et al. (2006; A. Burrows et al. 2006, private communication), and we found the data to be consistent with model temperatures in the range $T_i = 2200–2500$ K for A and $T_p = 2000–2200$ K for B, similar to the temperatures estimated from optical spectra (Jayawardhana & Ivanov 2006a). We were unable to constrain the gravity from the spectral shape, however, since the quality of the fit does not significantly change between $\log g = 3.5$ and $\log g = 6.0$.

Fortunately, there are a few atomic absorption features that appear to be more gravity-sensitive than the pseudocontinuum (Gorlova et al. 2003). In particular, the K i lines, seen in the ISAAC J-band spectra (Fig. 2), are sensitive to both temperature and gravity. In Figure 5 we present measurements of the equivalent width (EW) of the K i 1.25 $\mu$m line in Oph 1622 A and B, with our temperature estimates. For comparison, we also plot the EW for field dwarfs (from McLean et al. 2003) and EWs measured in DUSTY synthetic spectra. The major uncertainty in these measurements is the continuum, which is variable on small scales due to molecular absorption bands. From the figure, it is clear that the K i EWs of Oph 1622 A and B are significantly smaller than those of field dwarfs of similar atmosphere temperatures. According to the DUSTY models, a smaller EW is what we should expect for atmospheres of lower gravity. We therefore infer that the gravity is significantly lower for Oph 1622 A and B than for field dwarfs, and that Oph 1622 thus must be much younger than the field dwarfs.

Repeating the procedure for the other K i lines yields similar results. The EWs of these and other lines in the spectra are reported in Table 1.

From evolutionary models by Baraffe et al. (2002), one can derive the mass of an object once two of the three parameters (surface gravity, temperature, and age) are known. While the temperature is reasonably well constrained, the surface gravity is not. A low-mass object of effective temperature $T_p = 2100–2500$ K is expected to have a surface gravity of $\log g \simeq 3.6$ if the age is $\sim$1 Myr, $\log g \simeq 4.0$ if 5–10 Myr, and $\log g \simeq 5.3$ if in the field (Baraffe et al. 2002). Unfortunately, we find the DUSTY models to not be reliable enough at the level required to infer an accurate surface gravity. There seems to be a mismatch between the observed K i EWs for field objects from McLean et al. (2003) and the expected EWs from models (e.g., the K i 1.25 $\mu$m line in Fig. 5, but also the other K i lines not shown). The degree to which this mismatch is reflected among lower gravity objects is not known, since we lack a high-quality near-infrared spectroscopic library for

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**Table 1**

| Line          | EW$_A$ (Å) | EW$_B$ (Å) | $\lambda_0$ (µm) | $\lambda_1$ (µm) |
|---------------|------------|------------|------------------|------------------|
| Na i (1.14 $\mu$m) | 5.0 ± 1.6  | 6.1 ± 1.5  | 1.137            | 1.140            |
| K i (1.17 $\mu$m) | 1.2 ± 0.5  | 3.4 ± 0.5  | 1.167            | 1.171            |
| K i (1.18 $\mu$m) | 2.5 ± 0.5  | 4.0 ± 0.4  | 1.176            | 1.179            |
| Fe i (1.19 $\mu$m) | 1.1 ± 0.5  | 1.5 ± 0.5  | 1.188            | 1.191            |
| K i (1.25 $\mu$m) | 1.6 ± 0.6  | 2.6 ± 0.6  | 1.251            | 1.253            |
| Na i (2.21 $\mu$m) | 4.3 ± 0.8  | 4.4 ± 0.9  | 2.201            | 2.213            |

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**Fig. 4.—**ISAAC K-band spectra of Oph 1622 A and B, divided by the (pseudo)continuum. In addition to atomic features, the absorption train by molecular CO is identified.

**Fig. 5.—**(Pseudo)equivalent widths of the gravity-sensitive K i 1.25 $\mu$m line in Oph 1622 A and B, compared to DUSTY models (dashed lines) and observations of field objects (diamonds, from McLean et al. 2003). The estimated errors of the field objects are typically 0.3 Å, and for the models 0.8 Å (coming from the uncertainty of the continuum level). As is evident from this figure, the equivalent widths of Oph 1622 A and B are far below the expected values for field objects of the same spectral class, indicating low gravity and hence youth. Other K i lines in the spectra show the same trend.
young low-mass objects. In light of this unknown systematic error, we do not attempt to derive an age from the measured gravity. Instead, we assume that the age is comparable to other stars in the Ophiuchus star-forming region. Stars in the ρ Ophiuchi core region have ages 0.3–1 Myr (Luhman & Rieke 1999), while in the more extended Ophiuchus region ages have been estimated to be 0.3–10 Myr, with a median age of 2.1 Myr (Wilking et al. 2005). Combining our temperature estimates with the age estimate from Wilking et al. (2005), we find that the Baraffe et al. (2002) models give the mass estimates $M_8 = 13^{+4}_{-8} M_J$ and $M_8 = 10^{+4}_{-8} M_J$, where the main uncertainty is the assumed age range (1–10 Myr) and no systematic model uncertainty has been accounted for.

Our data are consistent with the near-infrared spectra of Oph 1622 obtained independently by Allers (2005) and Close et al. (2006). Allers (2005) report temperatures of 2300 and 2200 K and 2800 and 2700 K based on spectral energy distribution fitting (2006). Allers (2005) report temperatures of 2300 and 2200 K while in the more extended Ophiuchus region ages have been obtained independently by Allers (2005) and Close et al. (2006). Jayawardhana & Ivanov (2006a) find that the Oph 1622 binary is young. Instead, we use gravity-sensitive atomic K pseudocontinua in our spectra. Do not significantly constrain the gravity of the atmospheres. Instead, we use gravity-sensitive atomic K absorption in the J band and find the equivalent widths to be consistent with significantly lower gravities than field dwarfs of the same spectral type, providing the best evidence so far that the Oph 1622 binary is young.

3. Using our temperature estimates, the assumption that Oph 1622 is of the same age as other members of the Ophiuchus star-forming region, and the Baraffe et al. (2002) evolutionary tracks, we derive component masses of $M_8 = 13^{+4}_{-8} M_J$ and $M_8 = 10^{+4}_{-8} M_J$, where the major uncertainty contribution comes from the age (assumed to be 1–10 Myr).

The observations reported here were collected under the ESO program 277.C-5027. We gratefully acknowledge the help from Marten H. van Kerkwijk in getting his extraction routines to work, Aleks Scholz for general support, Adam Burrows for computing and sending us model spectra, and the ESO for rapidly executing our DDT request. We made extensive use of NASA’s Astrophysics Data System Bibliographic Services. This research was supported by an NSERC grant and University of Toronto research funds to R. J.

Facilities: NTT (SOFI), VLT (ISAAC).

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4. CONCLUSIONS

1. The infrared spectra of Oph 1622 A and B are consistent with model atmospheres of temperatures $T_g = 2350 \pm 150$ K and $T_g = 2100 \pm 100$ K, confirming previous estimates from optical spectra.

2. Model atmospheres, together with the pseudocontinua in our spectra, do not significantly constrain the gravity of the atmospheres. Instead, we use gravity-sensitive atomic K absorption in the J band and find the equivalent widths to be consistent with significantly lower gravities than field dwarfs of the same spectral type, providing the best evidence so far that the Oph 1622 binary is young.

3. Using our temperature estimates, the assumption that Oph 1622 is of the same age as other members of the Ophiuchus star-forming region, and the Baraffe et al. (2002) evolutionary tracks, we derive component masses of $M_8 = 13^{+4}_{-8} M_J$ and $M_8 = 10^{+4}_{-8} M_J$, where the major uncertainty contribution comes from the age (assumed to be 1–10 Myr).