

# SPECTROSCOPY OF A YOUNG BROWN DWARF IN THE $\rho$ OPHIUCHI CLUSTER<sup>1</sup>

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## ABSTRACT

We present observations of a young ( $\sim 3$ – $10$  Myr old) brown dwarf within the  $\rho$  Ophiuchi star-forming region. A low-resolution optical spectrum exhibits a spectral type of  $M8.5 \pm 0.5$  and strong  $H\alpha$  emission ( $W_\lambda \sim 60$  Å). After demonstrating the youth of this source through several additional lines of evidence, we place it on the H-R diagram and use the latest evolutionary tracks to derive a *substellar* mass of  $0.01$ – $0.06 M_\odot$ . A more accurate mass estimate will require tests of the evolutionary tracks and temperature scales at such young ages and late types.

*Subject headings:* stars: formation — stars: low-mass, brown dwarfs — stars: pre-main-sequence

## 1. INTRODUCTION

Brown dwarfs are an elusive class of object that can offer insight into several fundamental questions. Do substellar objects contribute significantly to dark matter? If extreme brown dwarfs (e.g., Jupiter) form only in circumstellar disks and low-mass stars form in both single and multiple systems, at what mass does the transition in formation mechanism occur? Do other physical properties of the protostellar system affect this transition? The issues that motivate research in brown dwarfs are reviewed in detail by Burrows & Liebert (1993).

Many searches for brown dwarfs have concentrated on open clusters. If cluster membership can be established for a brown dwarf candidate, then the cluster age and distance can be assigned to the object. The mass is then derived from evolutionary tracks. For example, three promising candidates in the Pleiades are PPL 15 (M6.5), Teide 1 (M8), and Calar 3 (M8). A detection of weak Li in the former implies that it is a transitional object near the hydrogen-burning limit (Basri, Marcy, & Graham 1996). All of the available evolutionary tracks also imply substellar masses of  $0.02$ – $0.07 M_\odot$  for Teide 1 and Calar 3 (Rebolo, Zapatero Osorio, & Martín 1995). Zapatero Osorio (1997) has recently discovered several additional candidates in deep CCD imaging of the Pleiades.

Young, embedded clusters offer unique advantages and disadvantages in the study of brown dwarfs. Very young brown dwarfs ( $\sim 1$  Myr) should be quite luminous ( $\log L/L_\odot \sim -2$  to  $-1$ ) and have properties similar to those of low-mass stars (e.g.,  $T_{\text{eff}}$ ,  $L$ ,  $[\text{Li}/\text{H}]$ ). Consequently, one could potentially detect brown dwarfs down to very low masses ( $\sim 0.01 M_\odot$ ) and examine their mass function and binarity in the context of a fairly compact, well-defined region of star formation. Contamination by background stars is also minimized by extinction within the cluster. X-ray emission,  $H\alpha$  emission, and Li absorption are likely to be strong in young brown dwarfs and should help in determining cluster membership. However, distinguishing young substellar objects from low-mass stars can be difficult, and we must rely on evolutionary tracks for deriving masses of free-floating objects. Finally, emission from circumstellar material can hamper the measurement of effective temperatures and bolometric luminosities.

As one of the nearest ( $\sim 160$  pc) young, embedded clusters,

the  $\rho$  Oph star-forming region is a prime hunting ground for newly formed brown dwarfs. Comeron et al. (1997, hereafter CRCT) have recently obtained  $3$ – $8 \mu\text{m}$  ISOCAM photometry of several low-mass candidates identified in ground-based near-IR imaging. After modeling the spectral energy distributions, they have used the derived luminosities in conjunction with theoretical evolutionary tracks to estimate masses for individual sources. Four brown dwarf candidates are identified, three of which are heavily embedded and impossible to observe in the optical. One source that exhibits little reddening ( $A_V < 2$ ) had been identified previously as either a foreground star or, if a  $\rho$  Oph member, a brown dwarf candidate (Rieke & Rieke 1990). We have obtained a low-resolution optical spectrum to determine its spectral type and optical photometry to test whether it is reddened. These data, along with the mid-IR excess reported by CRCT, establish the cluster membership of this object. We place it on the Hertzsprung-Russell (H-R) diagram and use the latest evolutionary tracks to discuss the question of its substellar nature.

## 2. OBSERVATIONS

We obtained an optical spectrum of  $\rho$  Oph 162349.8-242601 with the Red Channel Spectrograph at the Multiple Mirror Telescope on Mount Hopkins, on 1997 April 14 and 15. We used the  $270 \text{ g mm}^{-1}$  grating ( $\lambda_{\text{blaze}} = 7300$  Å) to obtain a spectrum from  $5000$  to  $9000$  Å. A  $2'' \times 180''$  aperture was used, providing a spectral resolution of  $\Delta\lambda = 18$  Å. Since this source is invisible on the optical television guider ( $m_V \sim 22.5$ ), we positioned an SAO star on the slit and offset to the coordinates of the  $\rho$  Oph source,  $\alpha = 16^{\text{h}}23^{\text{m}}49^{\text{s}}.8$  and  $\delta = -24^\circ26'01''$  (1950), as measured by Rieke & Rieke (1990). Three exposures of  $1800$  s were obtained during the two nights. To derive the sensitivity function of the array, we also observed the flux standards Feige 34, Ross 640, and BD +8 2015. The spectra were extracted from bias-subtracted frames, corrected for the sensitivity function, and wavelength calibrated with He-Ar-Ne lamp spectra. The three exposures were finally combined and smoothed to a resolution of  $\Delta\lambda \sim 25$  Å (see Fig. 1).

On 1997 June 8, we observed  $\rho$  Oph 162349.8-242601 with the Steward  $1200 \times 800$  CCD at the  $2.3$  m Bok Reflector on Kitt Peak. We obtained six exposures of this source with a nearly Mould  $I$ -band filter, each with an integration time of  $480$  s. We periodically observed the photometric standard Wolf 629 (Landolt 1992). After reducing the images and extracting photometry with standard procedures within IRAF, we applied

<sup>1</sup> Observations reported in this Letter were obtained with the Multiple Mirror Telescope operated by the Smithsonian Astrophysical Observatory and the University of Arizona.

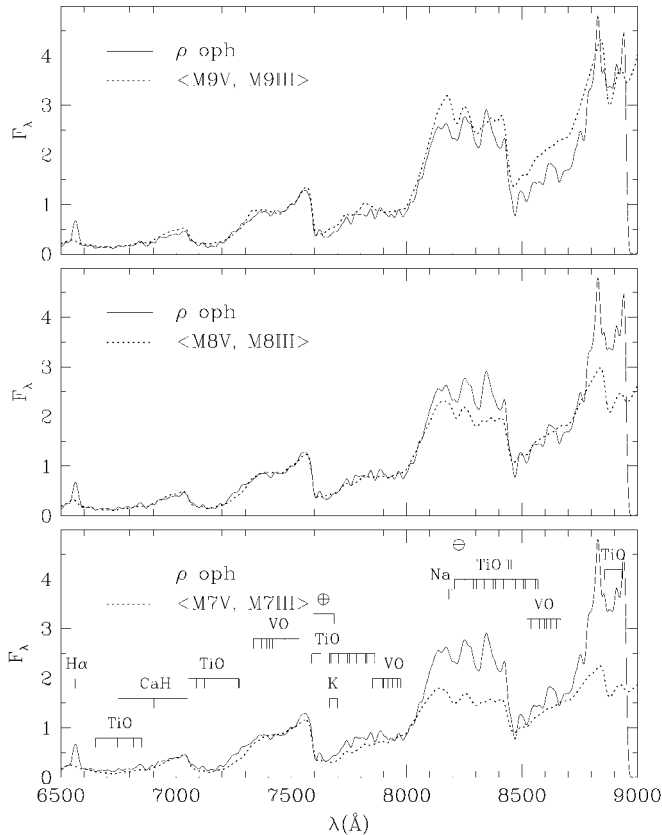


FIG. 1.—Optical spectrum of 162349.8-242601 plotted with averages of standard late-M dwarfs and giants. All spectra are normalized at 7500 Å.

an airmass correction ( $\sim 0.03$  mag) and transformed the photometry to the Cousins system ( $\sim 0.04$  mag). The latter was performed by convolving the transmission functions of the nearly Mould and Cousins *I*-band filters with the spectra of 162349.8-242601 and a standard dwarf of a spectral type similar to Wolf 629 (M4). On 1997 June 17, we used the Steward Observatory  $256 \times 256$  near-IR camera at the 1.6 m Bigelow Reflector to obtain *K*-band photometry. Using standard observing and reduction techniques, we measure  $K = 14.25 \pm 0.1$  for 162349.8-242601.

### 3. DISCUSSION

#### 3.1. Cluster Membership

In a discussion of embedded brown dwarf candidates in  $\rho$  Oph, Rieke & Rieke (1990) suggested that 162349.8-242601 may be a foreground dwarf since its IR colors imply little reddening. However, the membership of this object to the  $\rho$  Oph star-forming region is strongly supported by several new observations, the first of which is our measurement of H $\alpha$  emission ( $W_\lambda \sim 60$  Å) (see Fig. 1). Chromospheric emission in active late-M field dwarfs appears at a much lower intensity ( $W_\lambda \leq 15$  Å) (Liebert et al. 1992; Hawley, Gizis, & Reid 1996), whereas the circumstellar accretion disks of T Tauri stars often produce H $\alpha$  emission of  $\sim 100$  Å. The  $3\sigma$  detection of mid-IR excess emission toward this source by CRCT is also indicative of a young system with a circumstellar disk or envelope. Finally, we demonstrate in § 3.2 that the spectrum of 162349.8-242601 is intermediate between that of a dwarf and giant,

consistent with its pre-main-sequence nature. We conclude that this object is almost certainly young and associated with  $\rho$  Oph. We note that Casanova et al. (1995) do not detect this source in *ROSAT* observations of  $\rho$  Oph. With their upper limit of  $\log L_x/L_\odot \leq -6.1$ , we calculate  $\log L_x/L_{\text{bol}} \leq -3.6$  for this object, which is consistent with the typical ratio of  $-4$  measured for low-mass T Tauri stars.

#### 3.2. Spectral Type and Effective Temperature

Only the strongest features appearing in M stars are labeled in the spectrum of  $\rho$  Oph 162349.8-242601 in Figure 1. A more extensive line list (including telluric features) is found in Kirkpatrick, Henry, & McCarthy (1991). To classify the  $\rho$  Oph spectrum, we used the spectra of late-M standard stars provided by J. D. Kirkpatrick, where each spectral type is represented by the following stars: M7 V = VB 8; M7 III = VY Peg; M8 V = LHS 2243, LHS 2397a, LP 412-31, and VB 10; M8 III = IRAS 09540-0946; M9 V = BRI 1222-1222, LHS 2065, LHS 2924, and TVLM 868-110639; and M9 III = BR 1219-1336 and IRAS 15060+0947. We find features characteristic of both dwarfs and giants in the  $\rho$  Oph spectrum, which is not surprising given the surface gravity of a pre-main-sequence source. The same behavior is seen in late-type objects in Taurus and the Pleiades. In the optical spectrum of an M6 object in Taurus, Luhman et al. (1997) find that K I, Na I, and TiO/VO beyond 8200 Å are reproduced well by an M6 III spectrum, while CaH is intermediate between that of a dwarf and giant. They also present an IR spectrum that shows both dwarf (weak CO) and giant (weak Na) characteristics. In optical spectra of late-type Pleiades sources (M6–M8), Martín, Rebolo, & Zapatero Osorio (1996) observed weak Na I, which they attributed to nondwarf surface gravities. In 162349.8-242601 we also see weak, giant-like Na, while CaH, K I, and the continuum near Na I are intermediate between that of M8.5 V and M8.5 III. In future studies, these features should prove useful in distinguishing late field dwarfs from young, pre-main-sequence brown dwarfs.

For a given M subclass, we find that the closest match to the  $\rho$  Oph spectrum is achieved with an average of standard dwarf and giant spectra. These spectra for M7, M8, and M9 are shown in Figure 1 and clearly indicate a spectral type of  $M8.5 \pm 0.5$  for  $\rho$  Oph 162349.8-242601. The strength of VO near 7450, 7900, and 8600 Å is particularly indicative of very late types. We arrived at the same spectral type by using the spectral indices discussed by Martín et al. (1996) and references therein.

To place  $\rho$  Oph 162349.8-242601 on the H-R diagram, we must convert the M8.5 spectral type to an effective temperature. However, the temperature scale for late-M dwarfs is highly uncertain. Techniques in the derivation of temperature scales include fitting *K*-band photometry and bolometric fluxes to blackbodies (Berriman, Reid, & Leggett 1992), matching observed colors with those of synthetic spectra (Brett 1995), and fitting selected wavelengths of observed spectra to blackbodies (Jones et al. 1994). All of these studies imply relatively cool temperature scales, where  $T_{\text{eff}}(\text{M8 V}) \leq 2500$  K. On the other hand, Kirkpatrick et al. (1993) performed spectral synthesis of individual stars with the model atmospheres of Allard (1990) and estimated  $T_{\text{eff}}(\text{M8 V}, \text{M9 V}) = 2875, 2625$  K. Using Allard's latest NextGen synthetic spectra, Leggett et al. (1996) have repeated this experiment for stars as late as M6.5 V and arrive at a scale cooler by  $\sim 200$ – $300$  K. Luhman & Rieke

(1997) find that the Leggett et al. temperature scale is consistent with the empirical  $T_{\text{eff}}$  measurement of CM Dra and gives a reasonable age and mass for PPL 15 when coupled with the latest evolutionary tracks. If we extrapolate the Leggett et al. scale to later types, we arrive at  $T_{\text{eff}}(\text{M8.5 V}) \sim 2500$  K. This extrapolation is also consistent with the temperature of 2600 K adopted by Rebolo et al. (1996) for the M8 Pleiades brown dwarfs Teide 1 and Calar 3. Since the giant temperature scale, derived through angular diameter measurements, is warmer than the dwarf scale [ $T_{\text{eff}}(\text{M8 III}) \sim 2800$  K; Perrin et al. 1997], the temperature of a pre-main-sequence M8.5 object may be higher than that of a dwarf. If we assume that the intrinsic colors of a young M8.5 source fall between those of a dwarf and giant, then the evolutionary models of I. Baraffe (1997, private communication) predict that such a source will have a temperature that is  $\sim 100$  K greater than that of M8.5 V. If we combine this offset with  $T_{\text{eff}}(\text{M8.5 V}) \sim 2500$  K, we arrive at a temperature of  $\sim 2600$  K for 162349.8-242601, with an uncertainty of  $\pm 200$  K because of the spectral type ( $\pm 0.5$  subclass =  $\pm 100$  K) and temperature scale ( $\pm 100$  K).

### 3.3. Extinction and Bolometric Luminosity

Photometry of  $\rho$  Oph 162349.8-242601 was first obtained by Rieke & Rieke (1990), where they measured  $J = 15.4$ ,  $H = 14.7$ , and  $K = 14.2$  with uncertainties of  $\pm 0.2$ . In more recent observations, Barsony et al. (1997) have measured 10% photometry of  $J = 15.13$ ,  $H = 14.37$ , and  $K = 13.87$  in the CIT system. If we assume an intrinsic color of  $J - K = 1.14 - 1.21$ , as reported by Leggett (1992) for typical M8 V and M9 V stars, then the  $J - K$  measured for the  $\rho$  Oph source ( $1.2 \pm 0.3$ ,  $1.26 \pm 0.14$ ) implies an extinction of  $A_V \sim 0.5 \pm 0.5$  when combined with the extinction law of Rieke & Lebofsky (1985). With our new optical and IR photometry ( $I_C = 18.49 \pm 0.05$ ,  $K = 14.25 \pm 0.1$ ), we can make a more accurate estimate of the extinction. Luhman et al. (1997) find that the intrinsic colors of an M6 pre-main-sequence object in L1495E are similar to those of a typical M6 dwarf. Assuming that the intrinsic color of the  $\rho$  Oph source is similar to that of M8 and M9 dwarfs ( $I_C - K = 4.0 - 4.5$ ; Leggett 1992), our measurement of  $I_C - K = 4.24 \pm 0.11$  implies  $A_V = 0$  with an upper limit of 0.7, which is consistent with the values produced by  $E(J - K)$ . The presence of  $K$ -band excess emission can lead to an overestimate of extinction toward young stars, but this is not an issue here since we measure no extinction. To calculate the luminosity, we have used a bolometric correction of  $BC_J = 2.05$  as measured for M8 and M9 dwarfs (Kirkpatrick et al. 1993; Tinney, Mould, & Reid 1993). Since the optical spectrum of the  $\rho$  Oph source does not match perfectly with standard dwarf spectra, we adopt an uncertainty of  $\sim 0.15$  mag in this bolometric correction. With  $A_V = 0$  and an upper limit of 0.7,  $J = 15.25 \pm 0.25$ , and a distance modulus of  $6.1 \pm 0.1$  (Bertiau 1958; Whittet 1974), we arrive at  $\log L/L_\odot = -2.58 \pm 0.18$ . The diameter of the cluster is less than 1 pc, so the position of the source along the line of sight within the cloud is not important in the derivation of the luminosity.

### 3.4. Age and Mass

To examine the age and mass of  $\rho$  Oph 162349.8-242601, we have placed it on the H-R diagram in Figure 2 with the latest evolutionary tracks. Luhman & Rieke (1997) and Luhman (1997) discuss the comparison of available model interiors to the observations of YY Gem and CM Dra, globular clusters,

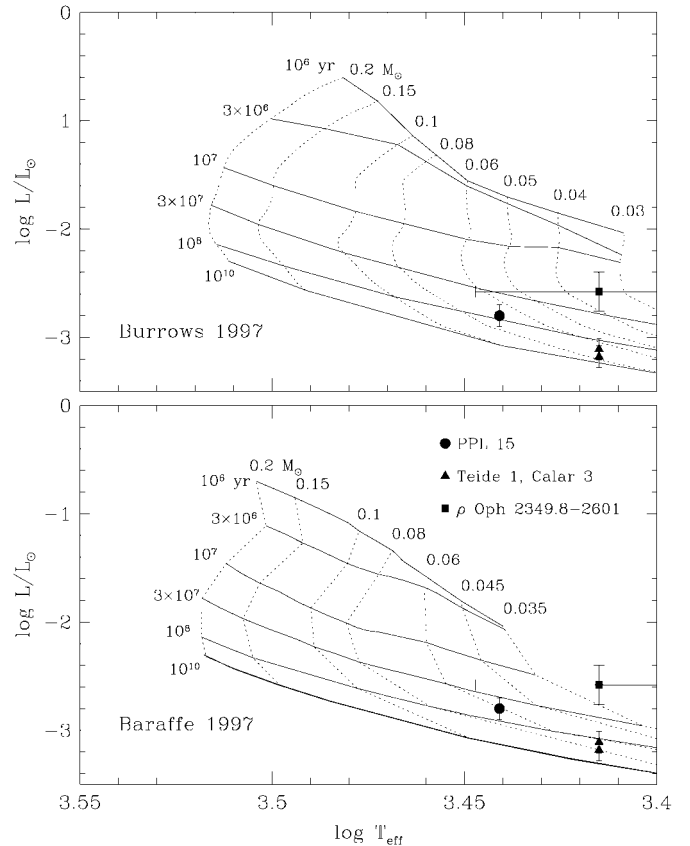


FIG. 2.—H-R diagram near the hydrogen burning limit. 162349.8-242601 is plotted with the temperature we estimate for a young M8.5 object on the evolutionary tracks of A. Burrows (1997, private communication) and I. Baraffe (1997, private communication). The Pleiades brown dwarfs PPL 15 (M6.5), Teide 1 (M8), and Calar 3 (M8) are shown for reference, using a dwarf temperature scale (without  $T_{\text{eff}}$  error bars).

embedded clusters, the Pleiades (particularly PPL 15), and the lower main sequence. On both observational and theoretical bases, the tracks of A. Burrows (1997, private communication) and I. Baraffe (1997, private communication) appear most appropriate for studying sources in the substellar regime. The age implied for 162349.8-242601 by Baraffe is  $\sim 3$ –10 Myr, whereas a slightly older age is produced by Burrows, both of which are older than the canonical cluster age of 1 Myr. However, it is unclear how seriously to take these age estimates given the uncertainties in the tracks at very young ages and cool temperatures. On the other hand, an H-R diagram for  $\rho$  Oph by Bouvier & Appenzeller (1992) shows sources as old as 10 Myr, so the age of 162349.8-242601 implied by the tracks is not unreasonable and may explain its low reddening.

From the models of Baraffe and Burrows we derive a mass of  $\sim 0.035 M_\odot$  for  $\rho$  Oph 162349.8-242601, with lower and upper limits of 0.01 and  $0.06 M_\odot$  given the uncertainties in the temperature of this object. A more accurate mass estimate will require observational tests of the low-mass tracks and late-type temperature scale, particularly at young ages. To place this  $\rho$  Oph source in the context of other recently discovered brown dwarfs, we have plotted PPL 15, Teide 1, and Calar 3 in Figure 2. Regardless of uncertainties in the temperature scale and tracks, 162349.8-242601 appears to be less massive than the three Pleiades sources and could be a very young precursor to Gl 229B ( $0.035$ – $0.05 M_\odot$ ) (Nakajima et al. 1995; Oppen-

heimer et al. 1995; Allard et al. 1996; Marley et al. 1996). This conclusion is in agreement with that of CRCT, derived independently by isochrone fitting of multiband photometry.

#### 4. CONCLUSION

We have presented compelling evidence of a young brown dwarf in the  $\rho$  Oph star-forming region. The youth and cluster membership of this source are strongly supported by its intense  $H\alpha$  emission ( $W_\lambda \sim 60 \text{ \AA}$ ), weak mid-IR excess emission (CRCT), and simultaneous dwarf and giant optical spectral features. After measuring a spectral type of M8.5 and placing the source on the H-R diagram, we used state-of-the-art evolutionary tracks to derive a mass of  $\sim 0.035 \pm 0.025 M_\odot$ ,

making it one of the youngest and least-massive brown dwarfs observed to date. These results add credence to the remaining  $\rho$  Oph brown dwarf candidates reported by CRCT, which will require IR spectroscopic confirmation because of their embedded nature.

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