The Astrophysical Journal, 493:909–913, 1998 February 1

A YOUNG STAR NEAR THE HYDROGEN-BURNING LIMIT[1]

K. L. Luhman,[2] César Briceño,[3,4,5] G. H. Rieke,[2] and Lee Hartmann[3]

Received 1997 June 25; accepted 1997 September 10

ABSTRACT

We show that V410 X-ray 3, toward the L1495E star-forming complex, is an object with a mass of 0.08–0.15 $M_{\odot}$ and an age of $\sim$1 Myr. Nonetheless, it has emerged from its natal cloud and can be studied in detail throughout the optical and near-infrared, providing new insights into the character of very young and low-mass objects. It has spectral characteristics intermediate between those of late dwarfs and giants (e.g., first-overtone CO typical of an M6 dwarf, but K I, Na I, and TiO/VO typical of an M6 giant and CaH intermediate between the luminosity classes). Its optical and IR photometric colors are consistent with those of an M6 dwarf. If the latest theoretical evolutionary tracks are valid at young ages and low masses, it appears that the hydrogen-burning limit at an age of $\sim$1 Myr occurs at a spectral type of M6–M7.

Subject headings: stars: formation — stars: fundamental parameters — stars: low-mass, brown dwarfs — stars: pre–main-sequence

1. INTRODUCTION

A broad variety of astrophysical issues have motivated searches for brown dwarfs (Burrows & Liebert 1993). However, for many years, no definitive detections were made (Stevenson 1991). This situation has changed dramatically with the discovery of the substellar companion Gl 229B (Nakajima et al. 1995; Oppenheimer et al. 1995) and of PPL 15 (M6.5), Teide 1 (M8), and Calar 3 (M8) in the Pleiades (Stauffer, Hamilton, & Probst 1994; Basri, Marcy, & Graham 1996; Rebolo, Zapatero Osorio, & Martín 1995; Zapatero Osorio, Rebolo, & Martín 1997). With a suite of prototype objects, the properties of relatively old brown dwarfs are becoming well defined to guide future search programs.

To establish the properties of brown dwarfs for comparison with theoretical predictions, we require objects over a large range of ages and masses. Newly formed brown dwarfs should be luminous and relatively easy to detect, but they are difficult to distinguish from low-mass stars. Unlike evolved brown dwarfs such as Gl 229B, young substellar objects are not drastically cooler than low-mass stars. Lithium depletion is useful in identifying brown dwarfs in the Pleiades since it marks the hydrogen-burning limit for stars at $\sim$100 Myr (Basri et al. 1996), but a similar test is not available for very young sources.

Since we must rely on evolutionary tracks to identify young brown dwarfs, we have carefully examined the translation of the theoretical hydrogen-burning limit into the observed spectral types. The Rosetta Stone for such a study is the young ($\sim$1 Myr), late-type (M6) source V410 X-ray 3 in L1495E within the star-forming Taurus-Auriga complex. This source was first identified in *ROSAT* observations by Strom & Strom (1994, hereafter SS94), making it one of the latest objects observed in Taurus at that time. Other young ($\leq$10 Myr) M6 sources observed to date include UX Tauri C and Ap J0323+4853 in α Persei (Magazzù, Martín, & Rebolo 1991; Zapatero Osorio et al. 1996). Since V410 X-ray 3 is nearby ($\sim$140 pc) and has no significant extinction or IR excess emission, we can accurately measure its bolometric luminosity and study it in both the optical and the IR. We have obtained low-resolution optical and IR spectra of V410 X-ray 3 to establish the spectral type and examine the behavior of gravity-sensitive features. We have placed the source on the Hertzsprung-Russell (H-R) diagram and used the latest evolutionary tracks to discuss the spectral type of the substellar boundary for very young sources.

2. OBSERVATIONS

We obtained *VRI* photometry for V410 X-ray 3 using the 2048 × 2048 thinned CCD mounted on the 1.2 m telescope of the Smithsonian Astrophysical Observatory at Mount Hopkins. The data were reduced using the standard IRAF routines for fixing bad pixels, bias-subtracting, and flat-fielding. Aperture photometry was performed using the APPHOT package. Instrumental magnitudes were transformed to the Cousins system using Landolt (1992) standard stars spanning a wide range of colors. The internal dispersion and systematic errors due to the transformation are at the $\pm$0.02 mag level. The new photometry is presented in Table 1, along with measurements of SS94 and Luhman & Rieke (1998).

K-band spectroscopy was performed on V410 X-ray 3 on 1994 December 9 using the near-IR long-slit spectrometer FSpec (Williams et al. 1993) at the Steward 2.3 m Bok reflector on Kitt Peak. The observing and data reduction procedures are discussed in detail by Luhman & Rieke (1998). We obtained an optical spectrum of V410 X-ray 3 with the Boller & Chivens spectrograph at the Bok reflector on 1996 November 7. We used the 400 g mm^{-1} grating ($\lambda_{\rm blaze}$ = 7506 Å) to obtain a spectrum from 5600 to 9000 Å with $\Delta\lambda$ = 6 Å and an integration time of 1200 s. To derive the sensitivity function of the array, we also observed Hiltner 102, a star whose intrinsic spectral distribution is known. The spectrum of V410 X-ray 3 was extracted from a bias-subtracted frame, corrected for the sensitivity function,

[1] Observations reported in this paper were obtained with the Multiple Mirror Telescope, operated by the Smithsonian Astrophysical Observatory and the University of Arizona.

[2] Steward Observatory, University of Arizona, Tucson, AZ 85721.

[3] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138.

[4] Also at Postgrado de Física, Universidad Central de Venezuela, Caracas, Venezuela.

[5] Also at Centro de Investigaciones de Astronomía (CIDA), Mérida, Venezuela.

TABLE 1

PHOTOMETRY OF V410 X-RAY 3

I_C	$(V-I)_C$	$(R-I)_C$	I_C-K	$J-H$	$H-K$	$K-L'$	K	Comments
13.53	...	2.27	3.04	0.57	0.44	...	10.49	1993 Jan 12[a]
...	...	...	...	0.94	0.37	...	10.77	1993 Mar 11[a]
...	...	...	...	0.69	0.40	0.05	10.54	1994 Dec 19[b]
14.07	4.18	2.25	...	...	...	...	...	1995 Dec 11
13.80	4.18	2.26	3.04	0.63	0.42	...	...	adopted
...	3.75	2.10	2.90	0.56	0.33	...	...	M6 V[c]
...	3.30	1.85	3.75	0.89	0.30	...	...	M6 III[d]
...	3.98	2.23	3.20	0.62	0.37	...	...	M6 V, $A_V = 0.6$
...	3.53	1.98	4.05	0.95	0.34	...	...	M6 III, $A_V = 0.6$

[a] SS94. *JHK* in CIT system.
[b] MMT *JHKL'*. *L'* is centered at 3.4 μm with a FWHM of 0.2 μm.
[c] M6 V colors from Leggett 1992.
[d] M6 III colors from Thé et al. 1990 and Frogel et al. 1978.

and wavelength calibrated using He-Ar and Fe-Ne lamp spectra.

An intermediate-resolution optical spectrum of V410 X-ray 3 was obtained on 1996 December 3 using the Blue Channel Spectrograph at the Multiple Mirror Telescope (MMT) on Mount Hopkins, equipped with the Loral 3072 × 1024 (15 μm square pixels) CCD binned by a factor 2:1 in the spatial direction. The spectrograph was configured with a 1200 g mm^{-1} grating and a 1''.5 × 180'' slit. This combination yielded a spectral resolution of 1.8 Å (0.50 Å pixel^{-1}) over the range ∼6000–7300 Å. Two 1800 s exposures were obtained of the source, each one followed immediately by an exposure of the He-Ne-Ar comparison lamp. High signal-to-noise exposures were also taken of standard stars with spectral types in the range M0–M6 (Allen & Strom 1995; Gliese 1969). All sources were observed at an air mass ∼1.5. The data were reduced using the standard IRAF procedures.

3. DISCUSSION

3.1. *Spectroscopic Results: Lithium Detection and Spectral Type*

Before discussing the other properties of V410 X-ray 3, we must first establish its membership to the L1495E star-forming region. The X-ray ($\log L_X/L_{bol} = -2.8$) and Hα ($W_\lambda = 16$ Å) emission of this source are indicative of a young star, but since the photometry and spectra imply little or no extinction, V410 X-ray 3 could also be a particularly active older foreground star. In the spectrum presented in Figure 1, we detect Li at $\lambda = 6707$ Å ($W_\lambda = 0.45$ Å). This result confirms the pre–main-sequence nature of this object and its membership to the L1495E region, against which it is projected on the sky.

In Figure 2, the optical spectrum of V410 X-ray 3 is compared with the spectra of Gl 406 (M6 V), SAO 141344 (M5 III), and VY Peg (M7 III) (provided by J. D. Kirkpatrick). Unfortunately, no M6 III spectrum was available. Only the strongest features appearing in M stars are labeled. The M6 V and an average of M5 III and M7 III spectra (referred to as M6 III in the following discussion) provide the closest matches to the spectrum of V410 X-ray 3. We estimate the spectral type to be M6 ± 0.5, which is consistent with the M6 type reported by SS94. *The remarkable aspect of the V410 X-ray 3 spectrum is the almost perfect match with M6 III.* As seen in Figure 2, CaH at 7000 Å is intermediate between M6 V and M6 III, while the other gravity-dependent features (K I, Na I, and TiO/VO beyond 8200 Å) are all reproduced well by the giant. The Na I line appears to be particularly sensitive to gravity. Martín, Rebolo, & Zapatero Osorio (1996) also observed weak Na I in late-type Pleiades sources (M6–M8), which they attributed to nondwarf surface gravities, even though these sources are much less luminous than V410 X-ray 3 and have surface gravities within a factor of ∼2 to those of dwarfs.

In Figure 3, the IR spectrum of V410 X-ray 3 is presented along with those of Gl 406 (M6 V), Gl 644C (M7 V), and R Lyr (M5 III). The strengths of Ca, CO, and the feature near 2.28 μm match those of M6 V or M7 V, but the Na is much weaker than in either standard. Na decreases in strength from dwarfs to giants, as seen in the M5 III spectrum, so the weak Na in V410 X-ray 3 is probably due to a low surface gravity, which is consistent with the nondwarf gravity implied by the optical spectrum. Greene & Meyer (1995) find similar behavior in *K*-band spectra of very young embedded stars in the ρ Ophiuchi complex. We also find this effect in an M5 star in L1495E, which has detectable Sc (2.195 μm) and weak Na, which are giantlike, while other features remain dwarflike, such as CO. Luhman & Rieke (1998) show that most of the stars in L1495E have IR spectra similar to those of dwarf comparison stars, whereas the spectrum of V410 X-ray 3 appears intermediate between

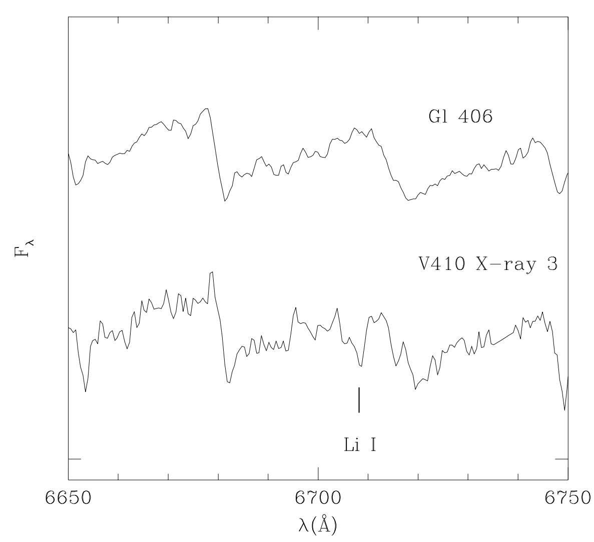

FIG. 1.—Li I region for V410 X-ray 3 in our MMT spectra. For comparison purposes we show the same spectral region for the standard star Gl 406 (M6 V).

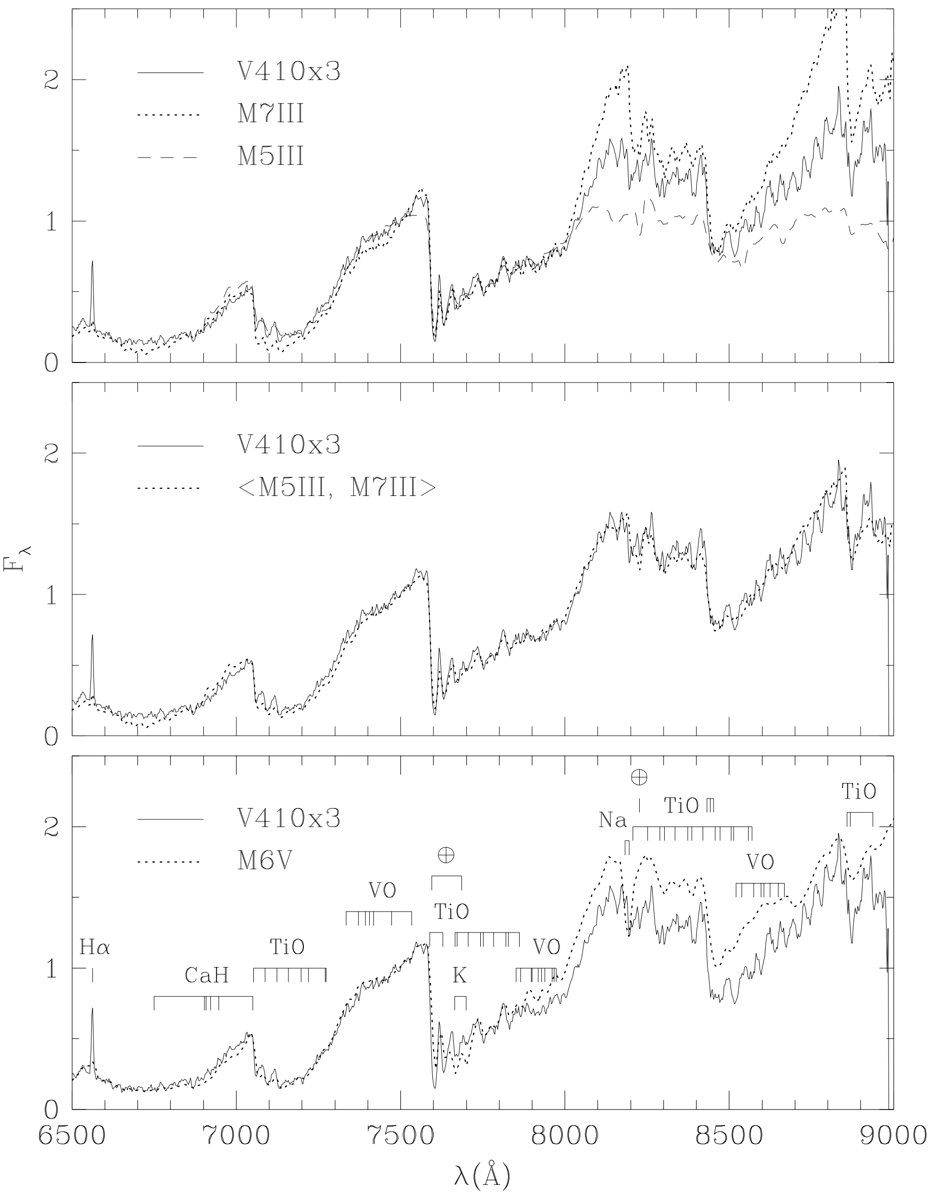

FIG. 2.—Optical spectrum of V410 X-ray 3 plotted with late-M spectral standards. All spectra are normalized at 7500 Å.

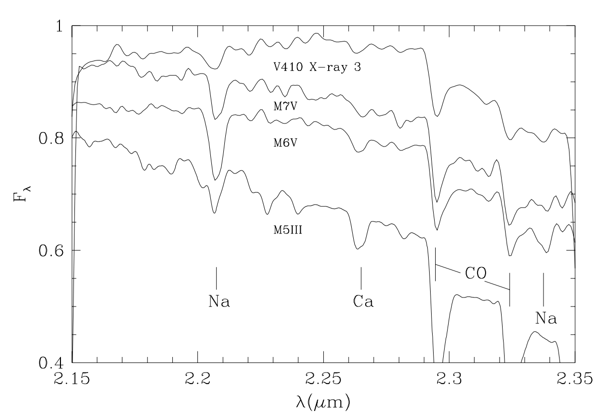

FIG. 3.—*K*-band spectrum ($R = 800$) of V410 X-ray 3 plotted with late-M dwarf and giant spectral standards, normalized at 2.2 μm with constant offsets.

a dwarf and a giant, consistent with the very young age implied by its position on the H-R diagram.

3.2. *Colors, Extinction, and Bolometric Luminosity*

In Table 1 we present all available photometry of V410 X-ray 3. It appears to be moderately variable, possibly because of starspots. To compute photometric colors for comparison with those of standard dwarf and giant colors, we have combined the data into colors labeled as "adopted" in Table 1 as follows: we take (1) $(V-I)_C$ from our measurement and $(R-I)_C$ as the average of our measurement and that of SS94; (2) $I_C - K$ from the data of SS94 for 1993 January 12, when simultaneous optical and infrared data were obtained; and (3) the average of SS94 *JHK* data and our measurements of 1994 December 19 to compute *JHK* colors (within the errors, the star was at the same brightness level for these two data sets). Standard M6

V (young disk) and M6 III colors are shown in Table 1, where we find that the colors of V410 X-ray 3 are matched closely by those of a normal M6 V dwarf reddened by $A_V = 0.6$ with the extinction law of Rieke & Lebofsky (1985). Alternative choices of standard colors (e.g., Bessell 1991) imply lower extinctions. We also find that the colors of M6 III do not match for any value of extinction. It is curious that the optical spectrum looks giantlike while the optical colors remain dwarflike.

In the same manner as Leggett et al. (1996), we have calculated $\log(L_{\rm bol}/L_\odot) = -1.23 \pm 0.1$ ($d = 140$ pc) by integrating the "adopted" broadband photometry in Table 1. If we apply the bolometric correction of a standard M6 V to *I* or *J* (Kenyon & Hartmann 1995), we arrive at nearly the same luminosity. The lack of excess emission at *V* and *L′* rules out significant contamination in the measured luminosity by a circumstellar disk.

3.3. *H-R Diagram*

To estimate the mass and age of V410 X-ray 3, we must use the H-R diagram in conjunction with theoretical evolutionary tracks. There are several sets of model interiors available. The tracks of D'Antona & Mazzitelli (1994) and Burrows et al. (1993) are shown in the upper panel of Figure 4, and newer calculations of Burrows (1997, private communication) and Baraffe (1997, private communication), using Allard's latest NextGen atmospheres, are given in the lower panel. Luhman & Rieke (1998) and Luhman (1997) discuss the comparison of the various models to the observations of YY Gem and CM Dra, globular clusters, embedded clusters, the Pleiades (particularly PPL 15), and the main sequence. The newer tracks appear to be well suited for studying sources near the hydrogen-burning limit, but we also show the tracks of D'Antona & Mazzitelli (1994) and Burrows et al. (1993) for reference since these calculations have been widely used.

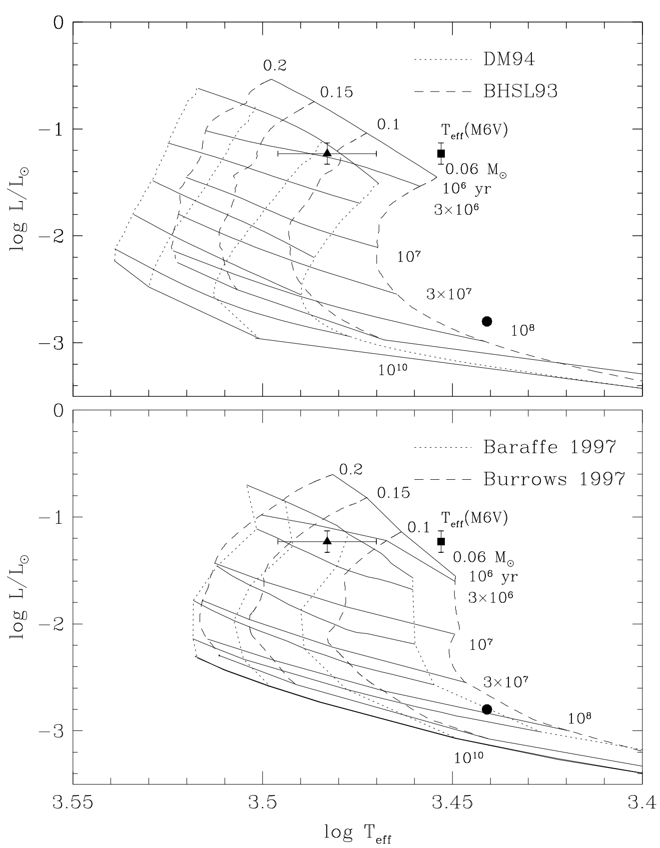

FIG. 4.—H-R diagram near the hydrogen-burning limit. V410 X-ray 3 is plotted with the Leggett et al. (1996) M6 V temperature (*square*) and and the theoretical temperature of a young M6 star (*triangle*). The error bar in effective temperature represents ±0.5 subclass. For reference, PPL 15 (M6.5) is also shown (*circle*).

The placement of V410 X-ray 3 on the H-R diagram now relies on the crucial step of converting the M6 spectral type to an effective temperature. Luhman & Rieke (1997) find that the Leggett et al. (1996) M dwarf temperature scale is consistent with the empirical $T_{\rm eff}$ measurement of CM Dra and also gives a reasonable age and mass for PPL 15 when coupled with the latest evolutionary tracks. Synthetic colors are produced by the latest tracks of Baraffe (1997, private communication) and the resulting $(I_{\rm C} - K)$–$T_{\rm eff}$ scale is quite similar to that of Leggett et al. (1996). When estimating $T_{\rm eff}$ for pre–main-sequence stars, it is customary to use a dwarf scale, so in Figure 4 we first plot the position of V410 X-ray 3 with $T_{\rm eff}$(M6 V) = 2840 K, as given by a fit to the Leggett et al. (1996) scale. The corresponding mass is ~ 0.07 $M_\odot$. However, since the optical spectrum matches well with M6 III and the IR spectrum appears intermediate between a dwarf and giant, the temperature of V410 X-ray 3 may fall between that of M6 V ($T_{\rm eff} = 2840$ K) and M6 III ($T_{\rm eff} = 3250$ K) (Ridgway et al. 1980; Perrin et al. 1997). If the intrinsic $I_{\rm C} - K$ of a young (1–3 Myr) M6 star is similar to that of M6 V, which is the case for V410 X-ray 3, then Baraffe (1997, private communication) predicts that such a source will have a temperature at ~ 200 K greater than that of M6 V. Figure 4 shows the position of V410 X-ray 3 with this temperature, where the mass implied by the latest tracks (~ 0.08–0.15 $M_\odot$) is now just above the hydrogen-burning limit. We therefore estimate that the hydrogen-burning limit occurs near M6–M7 for young, embedded stars.

4. CONCLUSION

We have presented observations of the late-type source V410 X-ray 3 in Taurus, which exhibits X-ray and Hα emission and Li absorption, clear signatures of youth. Because of its proximity, luminosity, and lack of heavy extinction, this source is a unique opportunity to study a low-mass young star from the optical into the IR. We show the following:

1. The colors are consistent with those of a slightly reddened dwarf ($A_V = 0.6$).
2. The optical spectrum matches well with M6 III, and the IR spectrum shows both dwarf (weak CO) and giant (weak Na) characteristics.
3. Using recent model interiors and atmospheres of Baraffe (1997, private communication), we estimate a temperature of ~ 200 K hotter than that of M6 V, thus implying a mass of ~ 0.08–0.15 $M_\odot$. However, the mass of this source could be as low as 0.07 $M_\odot$, if the Leggett et al. (1996) dwarf temperature scale is used.
4. Consequently, with the latest evolutionary tracks, the hydrogen-burning limit for young stars (~ 1 Myr) occurs at $\sim$M6–M7. However, the theoretical models are uncertain at very young ages and low masses and require observational tests.

We thank J. D. Kirkpatrick for access to his optical spectra of late-type stars. We are grateful to F. Allard, I.

Baraffe, A. Burrows, and F. D'Antona for providing their most recent calculations and useful advice. The work of K. L. and G. R. was supported by NASA grant NAGW-4083, under the Origins of Solar Systems program. The research of C. B. and L. H. was supported in part by NASA grant NAG 5-4282 and the Predoctoral Fellow program of the Smithsonian Institution, and by the Consejo Nacional de Investigaciones Científicas y Tecnológicas (CONICIT, Venezuela).

REFERENCES

Allen, L., & Strom, K., 1995, AJ, 109, 1379
Basri, G., Marcy, G. W., & Graham, J. R. 1996, ApJ, 458, 600
Bessell, M. S. 1991, AJ, 101, 662
Burrows, A., Hubbard, W. B., Saumon, D., & Lunine, J. I. 1993, ApJ, 406, 158
Burrows, A., & Liebert, J. 1993, Rev. Mod. Phys., 65, 301
D'Antona, F., & Mazzitelli, I. 1994, ApJS, 90, 467
Frogel, J. A., Persson, S. E., Matthews, K., & Aaronson, M. 1978, ApJ, 220, 75
Gliese, W., 1969, Veröff. Astron. Rechen-Inst. Heidelberg, 22, 1
Greene, T. P., & Meyer, M. R. 1995, ApJ, 450, 233
Kenyon, S. J., & Hartmann, L. 1995, ApJS, 101, 117
Landolt, A. U. 1992, AJ, 104, 340
Leggett, S. K. 1992, ApJS, 82, 351
Leggett, S. K., Allard, F., Berriman, G., Dahn, C. C., & Hauschildt, P. H. 1996, ApJS, 104, 117
Luhman, K. L. 1997, in ASP Conf. Ser., Brown Dwarfs and Extrasolar Planets, ed. R. Rebolo, E. L. Martín, & M. R. Zapatero Osorio (San Francisco: ASP), in press
Luhman, K. L., & Rieke, G. H. 1998, ApJ, 497, in press
Magazzù, A., Martín, E. L., & Rebolo, R. 1991, A&A, 249, 149
Martín, E. L., Rebolo, R., & Zapatero Osorio, M. R. 1996, ApJ, 469, 706
Nakajima, T., Oppenheimer, B. R., Kulkarni, S. R., Golimowski, D. A., Matthews, K., & Durrance, S. T. 1995, Nature, 378, 463
Oppenheimer, B. R., Kulkarni, S. R., Nakajima, T., & Matthews, K. 1995, Science, 270, 1478
Perrin, G., Coudé du Foresto, V., Ridgway, S. T., Mariotti, J.-M., Traub, W. A., Carleton, N. P., & Lacasse, M. G. 1997, A&A, in press
Rebolo, R., Zapatero Osorio, M. R., & Martín, E. L. 1995, Nature, 377, 129
Ridgway, S. T., Joyce, R. R., White, N. M., & Wing, R. F. 1980, ApJ, 235, 126
Rieke, G. H., & Lebofsky, M. J. 1985, ApJ, 288, 618
Stauffer, J. R., Hamilton, D., & Probst, R. G. 1994, AJ, 108, 155
Stevenson, D. J. 1991, ARA&A, 29, 163
Strom, K. M., & Strom, S. E. 1994, ApJ, 424, 237 (SS94)
Thé, P. S., Thomas, D., Christensen, C. G., & Westerlund, B. E. 1990, PASP, 102, 565
Williams, D. M., Boyle, R. P., Morgan, W. T., Rieke, G. H., Stauffer, J. R., & Rieke, M. J. 1996, ApJ, 464, 238
Zapatero Osorio, M. R., Rebolo, R., & Martín, E. L. 1997, A&A, 317, 164
Zapatero Osorio, M. R., Rebolo, R., Martín, E. L., & López García, R. J. 1996, A&A, 305, 519