1991ApJ...367L..23S

THE ASTROPHYSICAL JOURNAL, 367: L23–L26, 1991 January 20

SPECTROSCOPY OF TAURUS CLOUD BROWN DWARF CANDIDATES[1,2]

JOHN STAUFFER
Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138
TERRY HERTER
Cornell University, Astronomy Department, Space Sciences Building, Ithaca NY 14853
DONALD HAMILTON
California Institute of Technology, Caltech 105-24, Pasadena, CA 91125
GEORGE H. RIEKE AND MARCIA J. RIEKE
Steward Observatory, University of Arizona, Tucson, AZ 85721
RON PROBST
Kitt Peak National Observatory, P.O. Box 26732, Tucson, AZ 85726
AND
WILLIAM FORREST
University of Rochester, Department of Physics and Astronomy, Rochester, NY 14627
Received 1990 August 15; accepted 1990 October 24

ABSTRACT

We have obtained low-dispersion optical spectra for six objects and infrared spectra for two objects originally proposed to be brown dwarf members of the Taurus cloud population. None of the brown dwarf candidates shows definite Hα emission, and only two objects display molecular absorption bands. In one case, the weak TiO bands and Hα emission indicate a spectral type of K7–M0e, but these features may be caused by contamination from the nearby, bright primary HBC 370. In the other object, the TiO bands are definitely present but relatively weak indicating a spectral type of about M1–M2. These characteristics are unlike those expected for brown dwarfs; thus it appears that the brown dwarf candidates identified by Forrest et al. are much more likely to be heavily reddened background G or K field stars.

Subject headings: stars: formation — stars: late-type — stars: low-mass

1. INTRODUCTION

Forrest et al. (1989) identified nine faint, red objects as candidate brown dwarf members of the Taurus association. These objects were detected during an IR array imaging survey conducted at the IRTF using a 58 × 62 InSb infrared camera. The brown dwarf candidates had K magnitudes of order $K = 14$–15 and colors consistent with (but somewhat bluer than) what is expected for brown dwarfs of Taurus age, $\tau \simeq 10^6$ yr (see Cohen & Kuhi 1979). Four of the candidates had proper motions suggesting that they were likely members of the Taurus association. Because only a very small fraction of the Taurus dark cloud region was surveyed, the implied total number of brown dwarfs associated with the Taurus cloud would be very large if these identifications proved correct, suggesting that brown dwarfs could represent a significant fraction of the mass of the Galaxy.

The most likely alternative identification for these objects is that they are instead background, somewhat reddened field G or K dwarfs. Forrest et al. (1989) discounted this alternative based on (1) the proper motion measurements and (2) a calculation of the expected number of background stars, which suggested that the observed surface density of faint objects was 2–3 times greater than predicted.

It is clearly important to determine the true nature of thes brown dwarf candidates. Fortunately, spectroscopy offers decisive test of the two alternatives. According to any of th most referenced brown dwarf models (e.g., D'Antona & Mazz telli 1985; Nelson, Rappaport, & Joss 1986; Burrow Hubbard, & Lunine 1989), Taurus-age brown dwarfs shoul have effective temperatures less than 3200 K. Therefor barring unknown astrophysics, their optical and near-I spectra are expected to be similar to low-mass M dwarfs, an be dominated by strong molecular absorption bands due t TiO, VO, CaOH and H_2O. If, instead, the objects are reddene background stars, most of them should be hotter than abou 4000 K, and thus essentially no molecular bands are expectec A possible caveat to this simple scenario is that the photospheric spectra of low-mass Taurus members are sometime "veiled," resulting in optical continua with only weak absorption features which would be undetectable at low resolutio (Joy 1945; Rydgren, Strom, & Strom 1976). This veiling is nov generally attributed to the presence of accretion disks surrounding these stars (Kenyon & Hartmann 1987; Bertout Basri, & Bouvier 1988). In all such cases, however, the opticall veiled stars also have very strong emission lines (Hartigan et al 1990), thus still providing a clear distinction between th properties expected for Taurus members and those expectec for reddened background stars.

We have recently obtained spectra of the six best Taurus brown dwarf candidates from the Forrest et al. (1989) list. In § 2, we report details of these observations and provide our estimates of their spectral types. In § 3, we briefly discuss the implications of these results.

---

[1] Observations at the Palomar Observatory were made as part of a continuing collaborative agreement between the California Institute of Technology and Cornell University.

[2] Research reported here is partially based on observations made with the Multiple Mirror Telescope, a joint facility of the Smithsonian Institution and the University of Arizona.

TABLE 1

TAURUS BROWN DWARF CANDIDATES OBSERVED SPECTROSCOPICALLY

Forrest et al. ID Number	Nearest HBC Source	Offset from HBC	$J-H$	Proper Motion Member?	Spectral Type	A_V
1	370	3″.82E, 8″.28S	1.1	...	~M0 (≤M1)	≥1.2
2	370	13.5W, 4.75S	1.0	Y	≤K7	≥1.0
4	379	13.4W, 4.34S	0.46	Y	≤K7	≥0.
5	379	3.37E, 17.08S	0.7	Y	≤K7	≥0.5
6	379	1.64E, 29.68S	0.6	...	M1–M2?[a]	~0.5
17	376	4.50E, 9.97N	0.76	Y[b]	≤K7	≥0.

[a] The TiO bands at 6200, 7000, and 8000 Å indicate a spectral type of M1–M2, but the Na I 8183–8195 Å doublet (not resolved here) indicates a spectral type of M4.5 ± 1.

[b] Listed as YES in Forrest et al. 1989, but revised to MAYBE in Forrest et al. 1990.

2. SPECTROSCOPIC OBSERVATIONS

2.1. *Optical Spectra*

Six of the Taurus brown dwarf candidates were observed using the spectrograph attached to the 4-Shooter camera on the 200 inch (5.08 m) Hale telescope during 1990 January 1–3. A 300 l mm^{-1} grating was employed, which provided a spectroscopic resolution of about 15 Å and a wavelength coverage from roughly 6000 to 9000 Å. The entrance slit for the spectrograph was 2′ long and 1″.5 wide. The spectra were flat-fielded, sky-subtracted, and wavelength-calibrated using various routines within the IRAF environment (Tody 1986).

Table 1 lists the six sources for which we were able to obtain useful spectra, along with ancillary data for each source extracted from Table 1 of Forrest et al. (1989). We observed all four of the sources indicated by Forrest et al. (1989) to be proper motion members of Taurus. To estimate rough spectral types for these objects, we also observed a small number of nearby K and M dwarfs selected from the Gliese catalog, plus two well-established, bright members of Taurus (HBC 370 and HBC 376). Based on their appearance on the Palomar Sky Survey, the brown dwarf candidates observed have $R \simeq 18$–19.

Figure 1 shows a montage of spectra for six objects—three of the brown dwarf candidates; two Gliese catalog stars (GL 340A—spectral type K3 V, and GL 402—spectral type M5); and HBC 370 (spectral type K7: according to Herbig & Bell 1988; our spectra suggest M1 would be more appropriate). The spectra have been flux calibrated, although the absolute fluxes are not expected to be very accurate due to light cirrus during much of the observing run. The strong terrestrial O_2 absorption features at 6830 and 7600 Å have not been removed.

A slightly more complicated reduction process was needed for one object (Forrest 1) due to contamination by light from the nearby, bright HBC 370. For this object, the slit was rotated to 281° east of north in order to place both Forrest 1 and 2 along the slit (separated by 18″). However, scattered light from the much brighter HBC 370 produced a bright spectrum between the two candidates, separated from Forrest 1 by about 6″ (the seeing was about 2″.5). While Forrest 1 was clearly visible as a separate spectrum in the image frame, the original extracted spectrum was heavily contaminated by light from HBC 370. To remove this contribution, an extraction aperture symmetrically placed on the opposite side of the primary spectrum was defined. The spectrum from this aperture was subtracted from the original Forrest 1 + contamination spectrum to produce the spectrum discussed below.

The results of our observations are clear without the need of detailed analysis. Only one of the six objects shows definite molecular absorption bands (Forrest 6, Fig. 1 (*left*)). Forrest 1

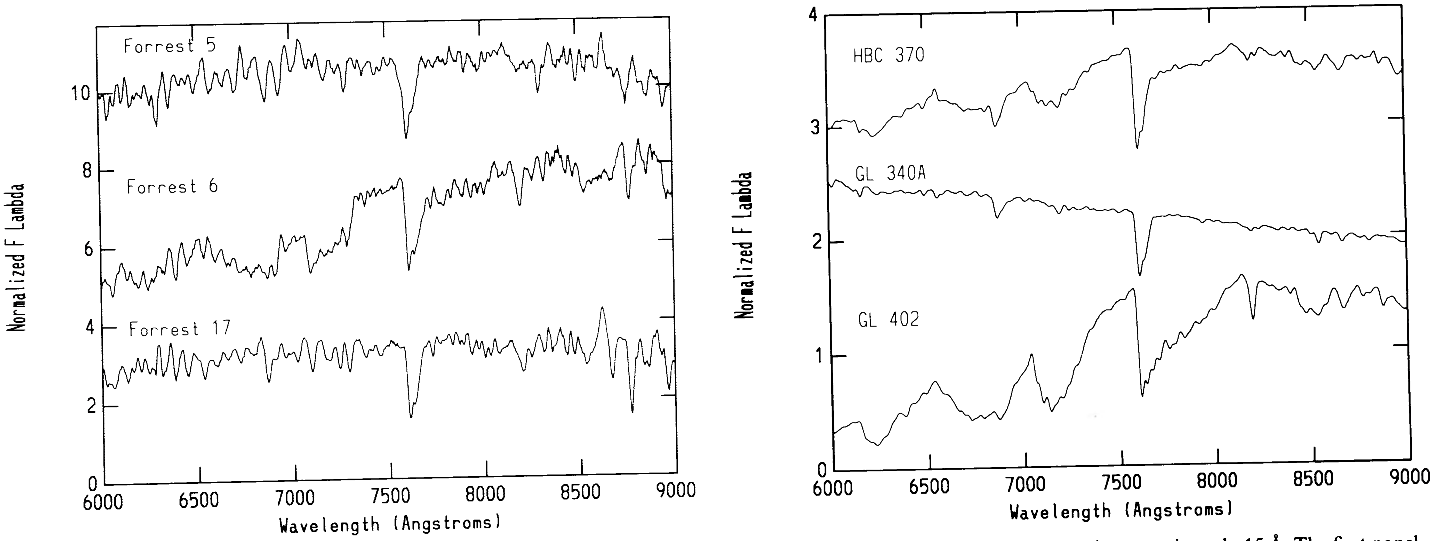

FIG. 1.—Spectra for six objects obtained during 1990 January with the Palomar 5 m telescope. The wavelength resolution is approximately 15 Å. The first panel shows brown dwarf candidates from Forrest et al. (1989), the second panel shows Gliese catalog stars observed as spectral standards plus a bright, typical Taurus member.

shows very weak TiO absorption and a weak Hα emission line, which may be caused by contamination by light from the primary. None of the other objects show even weak Hα emission. For the four stars with essentially continuous spectra, the lack of molecular bands indicate a spectral type of K7 or earlier (assuming these are conventional stars) and thus $T_{\rm eff} \geq 4000$ K. The effective spectral type for Forrest 1 as derived from the corrected spectrum (see above) is ∼M0. Because the TiO band strengths in the uncorrected spectrum are *weaker*, the spectral type for Forrest 1 must be earlier than that for HBC 370—that is, earlier than M1. For Forrest 6, the one object with definite TiO absorption, we estimate a spectral type of about M1–M2 by reference to the TiO bandstrengths of the Gliese catalog M dwarfs we observed. The Na I 8183–8195 Å doublet is quite strong in Forrest 6, suggesting a spectral type perhaps as late as M5, which would be inconsistent with the TiO band strengths. We consider the spectral type derived from the TiO bands better established than that estimated from a single atomic feature (whose strength could be affected by imperfect subtraction of the terrestrial Na I emission), but encourage additional spectra to be obtained for this star.

Some of the spectra appear to show weak emission lines other than Hα–in all cases, these features are most plausibly due to imperfect subtraction of strong night sky lines, such as the emission features at 6300 and 6363 Å in Forrest 17. While some T Tauri stars do show [O I] 6300 Å in emission, the [O I] lines are always much weaker than the Hα emission line (Cohen & Kuhi 1979); thus it is not plausible for us to attribute the apparent [O I] emission to the star because Hα is not in emission at our sensitivity limit (typical S/N at Hα is about 7, so with 15 Å resolution our 3 σ sensitivity for Hα is about 6 Å).

Because young brown dwarfs are expected to have surface temperatures comparable to those for mid-to-late main-sequence M dwarfs, we have a good knowledge of what their photospheric spectra should look like. A particularly good comparison can be made with GL 402 (type M5), whose optical and infrared colors indicate an effective temperature of about 3200 K. Very young brown dwarfs are predicted to have surface temperatures ≤3200 K, and thus should have molecular bands in their spectra as strong or stronger than those seen for GL 402 (Fig. 1 (*right*)). This is clearly not the case.

A similar conclusion can be reached by considering the coolest, well-studied Taurus members. Several Taurus members, including FN, FP, and XZ Tau, have spectral types of M3 or later and V magnitudes of 15.5 or brighter (Herbig & Bell 1988). The Forrest et al. (1989) candidates are at least 3 mag fainter than these stars, and thus if they are lower mass Taurus members of approximately the same age as FN, FP, and XZ Tau they should be considerably cooler. Instead, all of them have considerably higher effective temperatures, as inferred from their spectra. Given their effective temperatures and the assumption that they are at Taurus distance, the minimum mass these stars could have would be if they were on the main sequence, and thus considerably older than normal for a Taurus member, and heavily reddened. Because most of the candidates have spectral types of M0 or earlier, their corresponding minimum main-sequence masses are 0.45 $M_\odot$. Thus, even on empirical grounds—disregarding the possible errors in the brown dwarf models—the spectroscopic evidence suggests that it is unlikely that any of the objects observed could be very low mass Taurus members.

The spectral energy distributions for the program objects are somewhat redder than would be expected based on their inferred spectral types, presumably due to reddening. We can derive estimated reddenings for these objects, assuming they are normal stars, by comparing their spectral energy distributions with those for our Gliese catalog stars. For the four objects for which we only estimate the spectral type as earlier than K7, the reddening estimate we derive is only a lower limit. Our reddening estimate assumes the stars observed are dwarfs, as is expected for stars of this magnitude and galactic latitude (Bahcall & Soneira 1981). The result of this process is that the Taurus objects, on average, have a minimum reddening of order $A_V = 1.0$. Our spectral type and reddening estimates are provided in Table 1. These reddenings help explain the relatively red colors observed by Forrest et al. (1989). Note that none of the brown dwarf candidates have continuum energy distributions as red as GL 402, so that explanations of their smooth spectra as due to dust formation in their photospheres (as might be true for brown dwarfs) is not possible.

2.2. *Infrared Spectroscopy*

Two of the Taurus brown dwarf candidates were observed using a near-infrared spectrometer with the Multiple Mirror Telescope on 1989 December 11. The instrument was configured with 3″ diameter apertures and a 150 l mm^{-1} grating to provide a spectral resolution of ∼200 and 2 pixels per resolution element. It uses two rows of germanium diodes to provide a spectral range of 0.1 μm in a single grating setting with simultaneous observation of source in one entrance aperture and sky in the other. The roles of the entrance apertures are exchanged by wobbling the telescope every 60 s. Conditions were photometric.

Data were obtained by offsetting the MMT from nearby stars to the positions of the brown dwarf candidates. A series of short integrations allowed us to peak the signal and to refine the offset procedure to be sure the source was centered in the aperture (the maximum shift was 2″ from the nominal position). The instrument noise performance was compromised by the proximity of the sources to a nearly full Moon; however, the sky-subtraction procedure has removed any systematic effects from this cause.

Figures 2 and 3 compare the spectra obtained with that of VB 10 (spectral type M8 V according to Boeshaar 1976) measured on the Steward Observatory 90 inch with the same instrument. The strong absorption apparent in the low-luminosity star are not present in the Taurus objects.

As yet, there is no well-defined classification sequence for stellar spectra in this wavelength region. However, some guidance can be obtained from the behavior of the photometric H_2O index at 2 μm measured by Aaronson, Frogel, & Persson (1978). Assuming that the 1.4 μm steam feature has similar behavior, our data would imply that both Taurus objects are earlier than K7. Our unpublished partial comparison sequence shows directly that they are much earlier than M2.

The results of the infrared spectroscopy are therefore fully in agreement with those from optical spectroscopy. Given that there is no well-determined brown dwarf template spectrum, one could argue that some unanticipated effect dilutes some of the spectral features. The consistency of the two sets of data tends to make such possibilities considerably less likely.

3. DISCUSSION

We have obtained spectra for all of the highest probability brown dwarf candidates identified by Forrest et al. (1989).

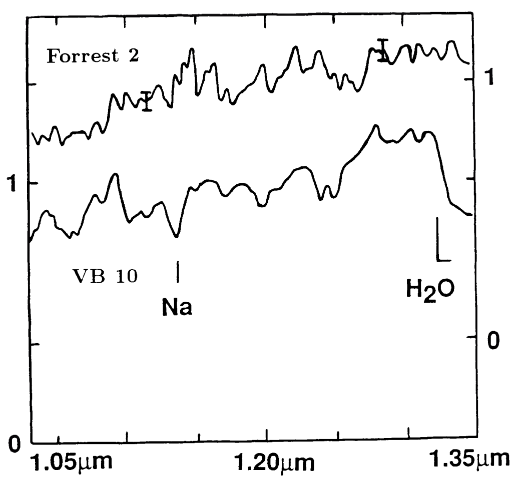

FIG. 2.—Comparison of near-IR spectra of Forrest 2 and VB 10. The lower trace is for VB 10, with zero point indicated at the lower left corner of the figure. It is at large signal-to-noise ratio and illustrates the absorptions that would be expected in a low-luminosity object, the strongest of which are steam at 1.33 μm and Na at 1.14 μm. The spectrum of Forrest 2 is offset for clarity as indicated by the zero on the *y*-axis; two typical error bars indicate the signal-to-noise ratio. No features are detected at a significant level.

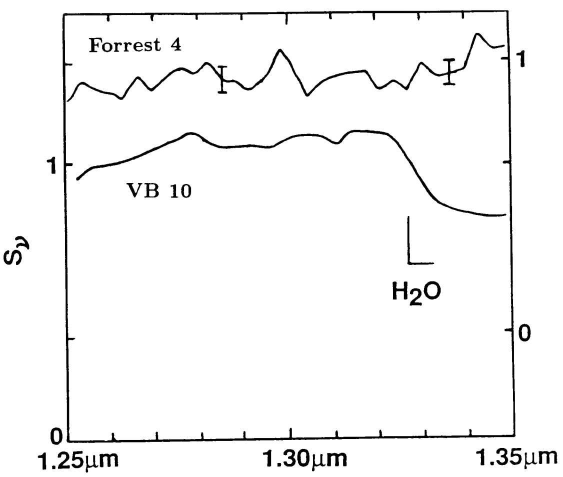

FIG. 3.—Comparison of near-IR spectra of Forrest 4 and VB 10. The figure is arranged as in Fig. 2. The steam feature at 1.33 μm is not detected in Forrest 4.

None of the six brown dwarf candidates which we have observed have spectra consistent with the low effective temperatures expected for brown dwarfs or for low mass, stellar members of the Taurus population. Our spectra are instead most consistent with these sources being background, reddened stars.

Our result does not exclude brown dwarfs from contributing significantly to the mass of Taurus, however. Forrest et al. (1989) surveyed only an extremely small fraction of the dark cloud population, so that only a very steeply rising mass function could have been detected. Taurus remains an appropriate region to continue brown dwarf surveys, particularly now that large-format IR arrays are becoming available.

We appreciate the assistance of Hans-Walter Rix and Douglas W. Kelly in reducing the infrared spectra. This work was partially supported by NSF grant AST 87-15236 and by the Kenneth T. and Eileen L. Norris Foundation.

REFERENCES

Aaronson, M., Frogel, J. A., & Persson, S. E. 1978, ApJ, 220, 442
Bahcall, J. & Soneira, R. 1981, ApJ, 47, 357
Bertout, C., Basri, G., & Bouvier, J. 1988, ApJ, 330, 350
Boeshaar, P. 1976, Ph.D. thesis, Ohio State University
Burrows, A., Hubbard, W., & Lunine, J. 1989, ApJ, 345, 939
Cohen, M., & Kuhi, L. 1979, ApJ, 41, 743
D'Antona, F., & Mazzitelli, I. 1985, ApJ, 296, 502
Forrest, W., Ninkov, Z., Garnett, J., Skrutskie, M., & Shure, M. 1989, in Proc. Third Infrared Technology Workshop, ed. C. McCreight, (NASA Tech. Memo. 102209), p. 221
———. 1990, in Strongly Coupled Plasma Physics, ed. S. Ichimaru (Yamada Science Foundation) (Elsevier), p. 33
Hartigan, P., Hartmann, L., Kenyon, S., Strom, S., & Skrutskie, M. 1990, ApJ, 354, L25
Herbig, G., & Bell, R. 1988, Lick Obs. Bull., No. 1111
Joy, A. H. 1945, ApJ, 102, 168
Kenyon, S., & Hartmann, L. 1987, ApJ, 323, 714
Nelson, L., Rappaport, S., & Joss, P. 1986, ApJ, 311, 226
Rydgren, A. E., Strom, S. E., & Strom, K. M. 1976, ApJ, 30, 307
Tody, D. 1986, in Instrumentation in Astronomy VI, ed. D. L. Crawford (SPIE Proc. vol. 627), p. 733