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THE UNIQUE SPECTRUM OF THE BROWN DWARF CANDIDATE GD 165B AND COMPARISON TO THE SPECTRA OF OTHER LOW-LUMINOSITY OBJECTS[1]

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ABSTRACT

The 6300–9000 Å spectrum of the brown dwarf candidate GD 165B is presented and compared to spectra of three of the lowest luminosity, red objects known: LHS 2924, LHS 2065, and PC 0025+0447. The features found in the spectrum of GD 165B may not correspond to the familiar molecular absorptions seen in these objects, and they do not match the molecular absorptions found in spectra of the Jovian planets. New, previously unidentified molecules may be present. Recent model energy distributions for M dwarfs do not predict spectra like the one presented here, so a temperature for this object is estimated using extrapolations to absolute magnitude versus temperature for low-mass stars. Two estimates are given for the location of GD 165B on the H-R diagram—one using our temperature estimate and the other using the temperature quoted in Zuckerman & Becklin. Neither data point yields an unambiguous classification as either star or brown dwarf for this unusual object. It can be concluded, nonetheless, that GD 165B has redder colors and fainter absolute magnitudes than any known main-sequence star—with a spectrum unlike that of any known M dwarf.

Subject headings: stars: individual (GD 165B) — stars: low-mass, brown dwarfs

1. INTRODUCTION

After it was first reported that ~30%–60% of the mass in the solar neighborhood could not be attributed to known matter (Oort 1960; Bahcall 1985), some astronomers proposed that the presence of many faint, previously undetected M dwarfs might explain the discrepancy. If not, there might be a sufficient, additional number of brown dwarfs, first theorized by Kumar (1963), to comprise the remainder of the missing mass. Oddly, until the early 1980s, GL 752B (VB 10) was still recognized as the lowest luminosity star, having held that title since its discovery almost 40 yr earlier (van Biesbroeck 1944). Three objects discovered during the course of Luyten's survey (see Luyten 1979), however, would later be recognized as objects of even later spectral type: LHS 2924 (Probst & Liebert 1983), LHS 2397a (Liebert, Boroson, & Giampapa 1984), and LHS 2065 (see Reid 1987; Bessell 1991).

Despite new claims that there is far less (or zero) missing mass than previously thought (Kuijken & Gilmore 1989; see alternate viewpoint in Bahcall, Flynn, & Gould 1992), various surveys implementing new techniques and technologies, especially at infrared wavelengths, have begun in the last decade to search for even fainter and redder objects. During a photometric search for low-luminosity objects orbiting white dwarfs, Becklin & Zuckerman (1988; hereafter BZ) discovered excess infrared radiation from the DA 4 (McCook & Sion 1987) white dwarf GD 165. Follow-up infrared imaging verified the presence of a faint companion, designated as GD 165B, approximately 4″ distant. At the time of its discovery, there was some question as to whether or not the object was merely a background source falling along nearly the same line of sight as the white dwarf. Fortunately, the large proper motion of GD 165A (0″.25 yr^{-1}; Luyten 1961) has in just a few years led to the confirmation of the two objects as a common proper motion pair (Zuckerman & Becklin 1992; hereafter ZB). Because of its extremely red colors and low luminosity, GD 165B is now generally regarded as the best brown dwarf candidate.

At present, a direct measurement of the mass is the only criterion which can distinguish a brown dwarf from a star. Unfortunately, the 4″ separation of the components implies an orbital period on the order of 1600 yr, so it will not soon be possible to calculate component B's dynamical mass. However, there may be other, more easily observable parameters which in principle could differentiate between stars and brown dwarfs, specifically red/near-infrared spectra, which have been obtained for many low-luminosity objects. In the case of the GD 165 system, the 4″ separation is, in another respect, advantageous: a spectrum of the secondary, uncontaminated by the light of the primary, can be acquired and can be compared to the spectra of other very red objects.

Table 1 lists all of those known dwarfs which have later spectral types than GL 65A and B (M5.5 and M6 V)—the reddest dwarfs for which spectra have been acquired *and* for which dynamical masses have been determined. GL 65A and B, also known as L726-8 and UV Cet, respectively, have approximately equal masses of 0.095 $M_\odot$, tantalizingly close to the upper mass limit, ~0.08 $M_\odot$, for brown dwarfs. (The purported substellar masses for Wolf 424A and B have been discussed by Henry et al. 1992 and Davidge & Boeshaar 1991. It now appears that the components are most likely stellar.) All dwarfs redder than GL 65A and B (1) are single, where a dynamical mass is impossible to determine, (2) are in binary or multiple systems with orbital periods of several hundreds to many thousands of years, or (3) have had masses determined from the technique of infrared speckle imaging—masses which, when the errors are considered, could put them on either side of the M dwarf/brown dwarf dividing line. Several objects in this third class are known, but they are too close to their

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[1] Observations reported here were obtained at the Multiple Mirror Telescope Observatory, a facility operated jointly by the Smithsonian Institution and the University of Arizona.

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primaries to yield uncontaminated spectra. These are listed in Table 2. Tables 1 and 2 thus represent the most complete compilation of low-luminosity objects currently known.

Kirkpatrick, Henry, & McCarthy (1991; hereafter KHM) and Kirkpatrick (1992) present spectra of many of the objects in Table 1. Since it is not known if the spectrum of a brown dwarf should be fundamentally different from that of a late-M star, it is conceivable that spectra of hot brown dwarfs already exist in the literature and have been labeled as M star spectra. On the other hand, it is possible that differences exist which would distinguish between them; i.e., a brown dwarf at the same temperature as a low-mass star should differ in τ, $\log g$, and possibly Z—any of which will produce changes in the spectra. To address this issue, a spectrum was obtained of GD 165B—the coolest, reddest entry in Table 1 and thus the most likely object to be a bona fide brown dwarf. The spectroscopic

TABLE 1

THE COOLEST "DWARF" SPECTRA

Object Name	Spectral Type[a]	Reference to Published Spectra	Note
H2118−4342	...	1	Single?
LHS 207	M6.5:	2	Single?
LHS 1317	M6.5:	2	Single?
LHS 523	M6.5	3, 4	Single?
G51−15 (LHS 248)	M6.5	3, 4	Single?[b]
LHS 191	M6.5	3, 4	Single?
LHS 292	M6.5	4	Single?[c]
GL 316.1 (LHS 2034)	M6.5	2	Single?
LHS 3332	M6.5	2	Single?
CTI 015607.7+280241	M6.5	4	Single?
CTI 092539.9+280018	M6.5	4	Single?
CTI 153915.6+280446	M6.5	4	Single?
CTI 174729.0+280322	M6.5	4	Single?
LHS 2351	...	5	Single?
LHS 2876	...	5	Single?
LHS 2930	M6.5	4, 5	Single?
LHS 2980	M6.5	4	Single?
LHS 3003	...	5	Single?
LHS 5142	M6.5	4	Single?
GRH 2208−2007	...	6	Single?
VB 8 (LHS 429)	M7	3, 4	Member of quadruple + system, [d] $P \sim 100,000$?? yr
LHS 3002	M7	5	Single?
LHS 2632	M7	4	Single?
LHS 2645	M7	4	Single?
ESO 207−61	...	7	Single?
HB 2124−4228	...	8	Single?
HB 2115−4518	...	8	Single?
BRI 0021−0214	...	9	Single?
CTI 115638.5+280002	M7	4	Single?
VB 10 (LHS 474)	M8	3, 4	Member of double system, [e] $P \sim 20,000$? yr
LHS 2397a	M8	4	Single?
RG 0050−2722	M8	4, 10	Single?
LHS 2243	M8	4	Single?
LH 0418+1339	...	11	Single?
GL 569B	M8.5	4, 12	Member of double system, $P \sim 500$ yr
CTI 012657.5+280202	M8.5	4	Single?
LHS 2065	M9	3, 4	Single?
LHS 2924	M9	3, 4	Single?
PC 0025+0447	M9.5	4, 13, 14	Single?
GD 165B	*very* late	4, 14	Member of double system, $P \sim 1600$ yr

[a] Given on an extension of the Boeshaar 1976 system, as reported in Kirkpatrick et al. 1991 and Kirkpatrick 1992.

[b] No companions detected to $M_K = 11.3$ at separations of 1 to 10 AU via infrared speckle imaging (Henry 1991).

[c] No companions detected to $M_K = 11.1$ at separations of 2 to 10 AU via infrared speckle imaging (Henry 1991).

[d] This is the fourth, widely separated component (GL 644C) in the system with GL 643 and GL 644AB. No companions detected to $M_K = 11.8$ at separations of 2 to 10 AU via infrared speckle imaging (Henry 1991).

[e] This is the low-luminosity, widely separated secondary of the GL 752AB system. No companions detected to $M_K = 12.1$ at separations of 5 to 10 AU via infrared speckle imaging (Henry 1991).

REFERENCES TO SPECTRA IN THE LITERATURE.—(1) Hawkins 1986; (2) Boeshaar 1992; (3) Kirkpatrick et al. 1991; (4) Kirkpatrick 1992; (5) Bessell 1991; (6) Gilmore, Reid, & Hewett 1985; (7) Ruiz, Takamiya, & Roth 1991; (8) Hawkins & Bessell 1988; (9) Irwin, McMahon, & Reid 1991; (10) Reid & Gilmore 1981; (11) Leggett & Hawkins 1989; (12) Henry & Kirkpatrick 1990; (13) Schneider et al. 1991; (14) This paper.

TABLE 2

LOW-MASS COMPANIONS FOR WHICH SPECTRA DO NOT EXIST

Name	Mass ($M_\odot$)	Note	Mass Reference
GL 623B	0.115 ± 0.040,[a]	$P =$ 3.73 yr	1
(LHS 417B)	0.078 ± 0.008		2
Ross 614B			
(GL 234B)......	0.080 ± 0.025	$P =$ 16.10 yr	1
G208-44B			
(GJ 1245C).....	0.075 ± 0.015	$P =$ 15.22 yr	1
LHS 1047B	0.060:,	$P =$ 4.63 yr	1
(GJ 1005B).....	0.055 ± 0.032		3
G29-38B	Unknown	Dust?	4–8

[a] Derived using speckle and astrometric data.

REFERENCES.—(1) Henry & McCarthy 1992; (2) Marcy & Moore 1989; (3) Ianna, Rohde, & McCarthy 1988; (4) Zuckerman & Becklin 1987; (5) Greenstein 1988; (6) Tokunaga, Becklin, & Zuckerman 1990a; (7) Graham et al. 1990; (8) Barnbaum, Misch, & Zuckerman 1992.

observations and the reduction of the data are detailed in § 2. The spectrum of GD 165B is compared to the spectra of other low-luminosity objects in § 3. Possible interpretations of the data are discussed in § 4, and conclusions are given in § 5.

2. OBSERVATION AND DATA REDUCTION

The spectrum of GD 165B was obtained on UT 1991 May 07 with the Red Channel Spectrograph of the Multiple Mirror Telescope (MMT; effective aperture 4.5 m). The observing setup is the same as that described in KHM. Since the object was invisible on the MMT TV acquisition screen, the slit was first centered on the position of GD 165A. and then the offsets given in BZ were used to move the slit to the position of GD 165B. The revised values of the offsets given in ZB differ only from the previous values by $0\farcs6$ in declination. Since the width of the slit employed was $2''$, this revision did not affect our ability to position the unseen secondary correctly on the slit.

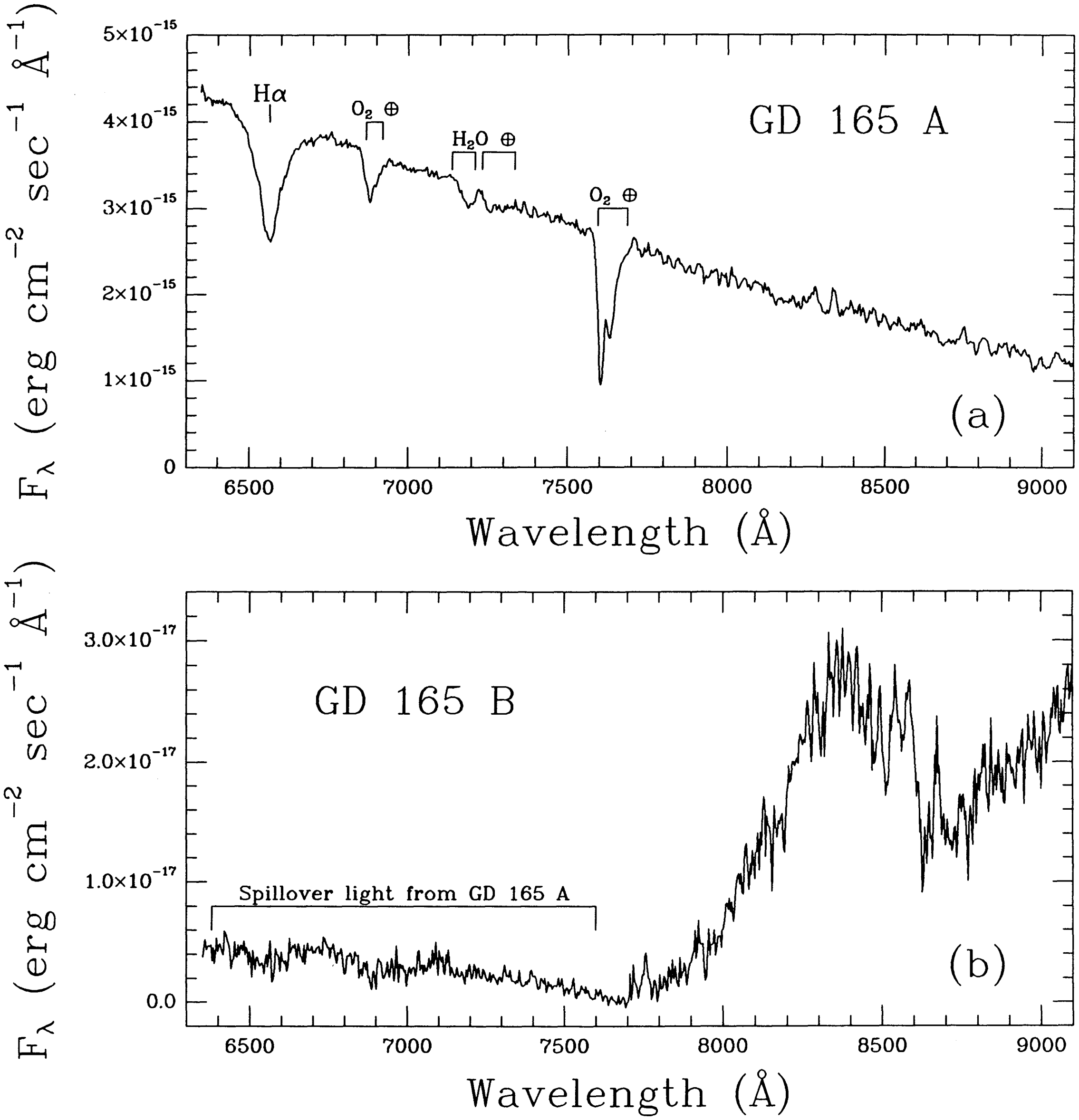

FIG. 1.—Spectra of the GD 165 system taken with the Red Channel Spectrograph of the Multiple Mirror Telescope. The resolution is 18 Å. Telluric absorption features have not been removed. (*a*) The spectrum of the DA4 white dwarf GD 165A. The broad Hα absorption is labeled. (*b*) The spectrum of the brown dwarf candidate GD 165B. Spillover light from GD 165A can be seen at the shortest wavelengths presented here. By 7500 Å this flux has dropped to almost zero, demonstrating that at longer wavelengths the spectrum of GD 165B is uncontaminated by the light of the primary.

All observations were obtained when the object was near the meridian, so differential refraction effects were negligible. As a result we were free to adjust the position of the slit on the sky to place the much brighter A component as far away from the slit as possible, while still allowing enough displacement along the direction of the slit to separate the spectrum of its spillover light cleanly from the spectrum of B on the CCD. For each exposure, the spectra were displaced on the CCD by 3″.2, and component A was ~1″ away from the edge of the slit. In all, a sequence of three 40 minute integrations was made. Afterward, GD 165A was placed in the slit and a 5 minute integration was taken.

Because of excellent seeing and guiding, the 3″.2 displacement of spectra on the chip was sufficient to eliminate almost all spillover light from the white dwarf into the spectrum of GD 165B. The spectra were reduced via the same procedures as those outlined in KHM, except that special care was taken to trace and define the extraction apertures so that this contaminant light was minimized. Only at short wavelengths, where the flux from the white dwarf is highest, is contamination of the GD 165B spectrum evident, and even here its effects are small. The 120 minute spectrum of GD 165B and the 5 minute spectrum of GD 165A are presented in Figure 1.

Because of excellent weather conditions on the night of observation, it is possible to extract I_C ($\sim I_{KC}$) magnitudes from the spectra in Figure 1. Values for $(F_\lambda)_{I_C}$ were determined over a rectangular bandpass whose cut-on and cutoff wavelengths correspond to the wavelengths at half maximum of the I_C filter: 7250 and 8750 Å. These fluxes were then converted to magnitudes by using 2550 Jy as the zero-magnitude flux (Bessell 1979). For a more complete discussion of this procedure, see Kirkpatrick et al. (1993). The resulting magnitudes are found to be $I_C = 14.2$ and 20.7 for GD 165A and B, respectively, and the parallax of the system is 0″.0278 ± 0″.0034 (ZB), giving absolute magnitudes of $M_{I_C} = 11.4$ and 17.9.

A lower (brighter) limit for the R_C magnitude of GD 165B can also be made if it is assumed that the mean flux level between 5700 Å (the filter cut-on) and 6350 Å is comparable to the flux level seen in our spectrum from 6350 Å to the filter cutoff at 7200 Å. As mentioned previously, nearly all of the flux seen in our spectrum from 6350 to 7200 Å is contaminant light from the primary, so the true flux of GD 165B will be substantially less than what is found here. Using a zero-magnitude flux of 3080 Jy (Bessell 1979), it is found that the magnitude must be fainter than $R_C = 21.5$, corresponding to an absolute magnitude of $M_{R_C} > 18.7$. If this object is assumed to have an $R-I$ color comparable to the latest M dwarfs [Leggett 1992 gives $(R-I)_C = 2.4$ for vB 8], then this implies that the absolute magnitude of GD 165B is $M_{R_C} \sim 20.3$. Photometric surveys like those of Reid & Gilmore (1982), Hawkins & Bessell (1988), Leggett & Hawkins (1988), and Kirkpatrick (1992), which have relied mainly upon R and I measurements, would have detected objects like GD 165B lying only within 9 pc for a limiting magnitude of $R \sim 20.0$ or within 6 pc for a limiting magnitude of $R \sim 19.0$. This illustrates that objects like GD 165B have not been missed because they are necessarily rare, but because they are exceedingly dim at these wavelengths.

3. COMPARISON TO THE SPECTRA OF OTHER LOW-LUMINOSITY OBJECTS

In Figure 2 are plotted the spectra of GD 165B and three of the lowest luminosity, red objects known: PC 0025+0447, LHS 2065, and LHS 2924, the last of which has spectral identifications marked. Observation and reduction procedures for the spectra of LHS 2924 and LHS 2065 have been discussed elsewhere (KHM). The spectrum of PC 0025+0447 (Schneider et al. 1991) was acquired on UT 1991 October 17 with the Red Channel Spectrograph at the MMT with the same setup described in § 2 above. Like GD 165B, this object was invisible on the MMT TV acquisition screen, but in this case the position given in the discovery paper quotes an error of 5″. To improve our chances of finding this object, the slit was first centered on a nearby bright star, SAO 109220, then offsets were used to point to the position given in Schneider et al. (1991). A "quick" 5 minute integration on this position revealed no evidence on the CCD of an unseen object, so the slit was moved 2″ (the slit width) to the east, and another 5 minute integration taken. Again, no spectrum was seen. After several failed attempts to find the object to the west, a faint spectrum was finally revealed at a location 4″ east of the original position. Believing that the object was perhaps lying near the edge of the slit, the slit was moved another 1″ east. The spectrum recorded there was, in fact, brighter, so this position was retained for all subsequent exposures. In all, nine 20 minute integrations were made. The spectrum of PC 0025+0447 shown in Figure 2 is the addition of all 3 hr of integration.

PC 0025+0447 is unique in its own right. Based on the fact that its VO bands, most noticeably the one between 7851 and 7973 Å, are somewhat stronger than those of LHS 2924 and LHS 2065, we classify this object as an M9.5. Unlike LHS 2924, which has weak Hα emission, and LHS 2065, which has Hα emission similar in strength to other dMe's, PC 0025+0447 has an Hα equivalent width 10 times larger than any dwarf M star known (Schneider et al. 1991). Apart from the unusual emission feature, this object seems, nonetheless, to be a continuation of the spectral sequence to temperatures cooler than that of LHS 2924 and LHS 2065.

It is clear that the spectrum of GD 165B, however, does not closely resemble the three other spectra in Figure 2 or, in fact, any of the spectra of low-mass stars presented in KHM. (No statement can be made about the presence or absence of Hα emission since no flux attributable to the B component is detected at this wavelength.) Notably absent are the TiO absorptions at 8432 Å and 8859 Å, which are quite strong for late M dwarfs. The close Na I doublet at 8183 and 8195 Å may be present, but this is an uncertain identification since at 18 Å resolution this will be blended with telluric water absorption between 8164 and 8177 Å. Absorptions by TiO may be marginally present at 8303 and 8510 Å, while the obvious absorption at 8624 Å may correspond to VO, although much stronger than the VO absorption seen in an M9 or M9.5 spectrum. These features could, therefore, be caused by the same molecular species which dominate the spectra of late M dwarfs, only that the absorption profiles and strengths are different due to the lower temperature of this object. On the other hand, it is also possible that new sources of opacity not present in the spectrum of an M9 or an M9.5 object are strongly affecting the spectrum of GD 165B from 8700 Å to our cutoff of 9000 Å. Before any of these features are adequately identified, a higher signal-to-noise spectrum at higher resolution is required.

Assuming that the object is a cooler version of LHS 2924, the extreme redness and unique appearance of its spectrum would suggest a classification later than M10, since we have classified PC 0025+0447 as an M9.5. Since there are few spectral features on which to base a true spectral classification and

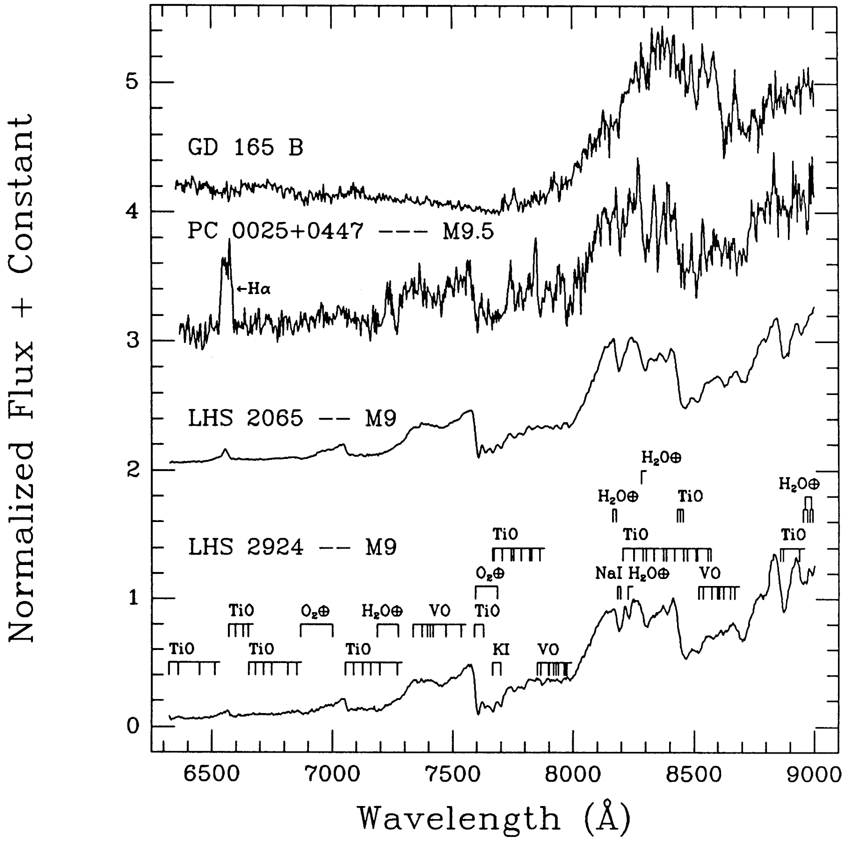

FIG. 2.—Spectra of the four latest "dwarfs" known. The spectra were taken at the Multiple Mirror Telescope and have a resolution of 18 Å. The flux (in units of F_λ) for each spectrum has been normalized to unity at 8250 Å (where there seems to be a common opacity minimum), and integral offsets have been added to separate the spectra vertically. Absorptions by telluric O_2 and H_2O have not been removed. Features listed in Kirkpatrick et al. (1991) are identified in the spectrum of LHS 2924. Note the continuation by PC 0025+0447 of the familiar M dwarf sequence to even cooler temperatures, as evidenced by increased absorption by VO. Also note the lack of similarity between the spectrum of GD 165B and any of the other spectra presented here.

currently no other spectra to bridge the gap between the M9/M9.5 objects and GD 165B, we are forced to delay classification until other such objects are discovered. Only when the spectral type can be *quantified* should a type be assigned.

4. DISCUSSION

Table 3 gives observed colors and absolute magnitudes for GD 165B and a sequence of M dwarfs. (BZ give $J = 15.75$ for GD 165B, but this and the other J values in their table are on the CIT system, *not* the IRTF system; Zuckerman 1992. All infrared photometry listed in Table 3 has been placed on the AAO system using the transformations given in Leggett 1992.) These data clearly show that GD 165B has extremely red colors and extremely low luminosity, indicative of a very cool temperature. Also given for the first eight objects in Table 3 are the temperatures derived from fits of observed 0.6–1.5 μm

TABLE 3

COLORS, ABSOLUTE MAGNITUDES, AND TEMPERATURES FOR A SEQUENCE OF M DWARFS[a]

Name	Spectral Type	$I-J$	$J-H$	$J-K$	M_I	M_J	Temperature (K)
GL 411	M2 V	1.13	0.54	0.75	8.32	7.19	> 3500
GL 273	M3.5 V	1.40	0.52	0.77	9.33	7.93	3500
GL 213	M4 V	1.47	0.53	0.78	9.86	8.39	3375
G208-44AB[b]	M5.5 V	2.19	0.52	0.89	11.59	9.40	3125
G208-45	M6 V	2.15	0.50	0.89	12.10	9.95	3125
GL 406	M6 V	2.31	0.62	0.98	12.63	10.32	3000
GL 752B	M8 V	2.74	0.67	1.11	13.98	11.24	2875
LHS 2924	M9	3.38	0.65	1.12	15.09	11.71	2625
GD 165B	*very* late	4.7	1.09	1.84	17.9	13.2	see text

[a] For data on the first eight objects refer to Kirkpatrick et al. 1993; see text for data on GD 165B. I magnitudes are given on the Kron-Cousins system; J, H, and K magnitudes have been transformed to the AAO system. (The J magnitudes listed in Table 1 of Becklin & Zuckerman 1988 are on the CIT system, not the IRTF system, despite what is implied by their second footnote (Zuckerman 1992).)

[b] Composite spectrum, colors, and magnitudes assumed to be dominated by the A component.

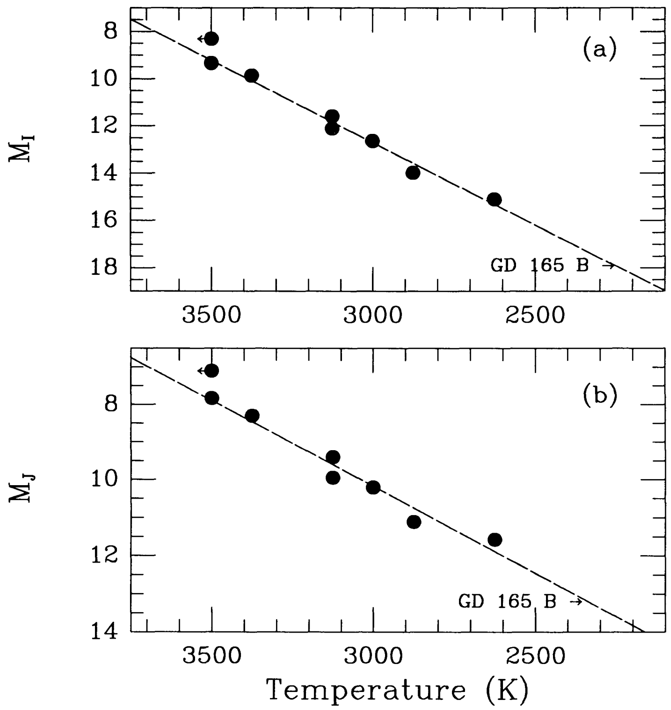

FIG. 3.—Absolute magnitude vs. temperature for those dwarfs presented in Table 3. The dashed line represents a linear least-squares fit to the data, excluding the upper limit point for GL 411. The absolute magnitude of GD 165B is indicated with an arrow. (*a*) M_I vs. temperature. The extrapolation gives $T \approx 2250$ K for GD 165B. (*b*) M_J vs. temperature. The extrapolation gives $T \approx 2350$ K for GD 165B.

spectra to Allard's (1990) model energy distributions for M dwarfs (Kirkpatrick et al. 1993). The models do not currently predict a spectrum like that of Figure 1*b*, but some idea of the temperature of this object can be estimated by extrapolating the trends of M_I and M_J with temperature to the absolute magnitudes calculated for GD 165B. These extrapolations, which provide only a crude temperature estimate for GD 165B, are shown in Figure 3. A linear least-squares fit is shown for each graph, where the lower limit to the temperature for GL 411 has been ignored. The trend of M_I versus temperature suggests $T \approx 2250$ K for GD 165B, whereas the trend of M_J versus temperature suggests $T \approx 2350$ K. As a result, the rounded value of $T = 2300 \pm 100$ K will be adopted as the temperature estimate of GD 165B based on these fits. ZB derive an estimate of the temperature based on blackbody fits to the observed colors with additional allowance for the H_2O blanketing seen in the spectrum taken by Tokunaga et al. (1990b; the spectrum itself is unpublished). Their result is $T = 1800 \pm 200$ K, cooler by 500 K than the temperature derived here. This discrepancy is not unexpected, however. As noted in Kirkpatrick et al. (1993), when compared to temperatures derived from fits to the models, temperatures based on various blackbody fitting techniques, though in good agreement for early M dwarfs, are lower by up to 500 K for late M dwarfs such as GL 752B (vB 10).

For some range of temperatures, the spectra of cool objects should begin to bridge the gap between the observed spectra of late M dwarfs (dominated in the red and infrared by molecules such as VO, TiO, H_2O, and CO) and the observed spectra of Jupiter and Saturn (which are dominated in this region by molecules such as CH_4 and NH_3). This transition is apparently not a simple one. Absorption by TiO cannot be distinguished in the spectrum of GD 165B, although VO may still be present. Absorptions by CH_4, which appear prominently in the spectra of Jupiter and Saturn, would be present in a broad band extending from 7600 to 8200 Å (Wolstencroft & Smith 1979), in another band extending from 8500 to 8750 Å with a minimum at ~8600 Å, and in another, more prominent band with a sharp cut-on near 8800 Å, a gradual cut off near 9100 Å, and two minima at ~8825 and 8873 Å (Owen 1969). (For full coverage of this region, refer to the laboratory spectra of methane in Dick & Fink 1977 and the observational spectra of Jupiter in Taylor 1965.) Although these wavelengths correspond to the same general regions where absorption occurs in the spectrum of GD 165B, the shape of the bands and the locations of the minima do not match (even for the laboratory spectra taken over a range of physical conditions), indicating that methane is not the absorber. Moreover, as Lunine, Hubbard, & Marley (1986) state, the dominant carbon species should switch from CO to CH_4 only at temperatures around 1000 K—much cooler than that found for GD 165B. Absorption by ammonia, though weaker than methane, is also found between 7500 and 9000 Å but is expected only at even lower temperatures. In other words, the molecules found in M dwarf spectra may no longer be prominent, and the molecules found in planetary spectra do not appear at temperatures as warm as GD 165B. The features found in our spectrum are likely to be new, presently unidentified molecular absorptions.

Until a broader wavelength coverage is obtained for spectra in the infrared, the bolometric luminosity of this object will be difficult to estimate. Greenstein's (1989) best estimate, when updated to reflect the currently accepted distance of 36 pc, is $1.2 \times 10^{-4}\ L_\odot$, in excellent agreement with the estimate of $1 \times 10^{-4}\ L_\odot$ by ZB, who quote an uncertainty of ~40%. Figure 4 shows the H-R diagram for M dwarfs using data from Kirkpatrick et al (1993). Also shown are the theoretical zero-age main sequence of D'Antona & Mazzitelli (1985) and the sequences, based on two different equations of state, of Dorman, Nelson, & Chau (1989). Two positions for GD 165B are given in Figure 4. The first uses the temperature derived here, and the second uses the temperature estimated in ZB; for both, the luminosity estimate of $1 \times 10^{-4}\ L_\odot$ is adopted. Both points fall near the region occupied, according to theory, by stellar objects marking the end of the main sequence; however, considering the errors in the plotted quantities, both points are near enough to the stellar/substellar dividing line (~$0.08\ M_\odot$) to leave the true nature of GD 165B ambiguous.

5. CONCLUSIONS

It has been shown that the 6300–9000 Å spectrum of GD 165B is unlike that of any known M dwarf. Bands of VO, which appear only in the lastest M dwarfs may be present, though significantly stronger. The estimated temperature is low enough that new molecular absorptions, not found in warmer spectra like that of LHS 2924, may be appearing. The temperature is not cool enough, however, for this spectrum to begin to resemble the observed spectra of Jovian planets. At present, the precise location of GD 165B on the H-R diagram is not known, due to large uncertainties in calculating both the temperature and the bolometric luminosity. The temperature will be accurately known only once theoretical energy distribu-

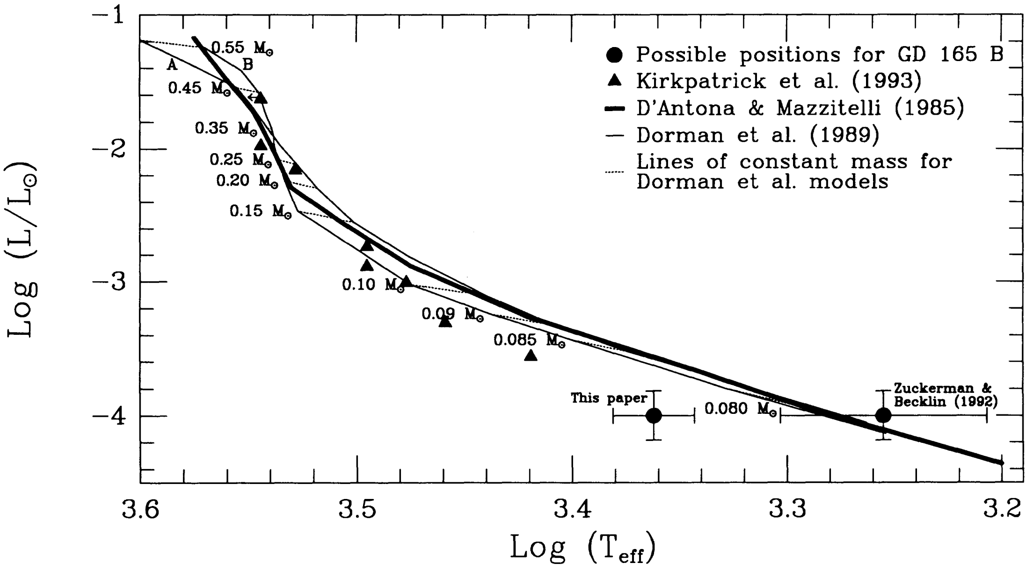

FIG. 4.—H-R diagram for M dwarfs and GD 165B. This figure is an adaptation of Fig. 6*b* from Kirkpatrick et al. (1993). Indicated are the theoretical zero-age main sequences of D'Antona & Mazzitelli (1985—*heavy line*) and of Dorman et al. (1989, models A and B—*lighter lines*). Lines of constant mass are indicated by dashes on the Dorman et al. models. (For a comparison to the theoretical models of Burrows, Hubbard, & Lunine 1989, refer to Fig. 6*a* of Kirkpatrick et al. 1993.) Triangles represent the first eight objects listed in Table 3, and the circles give two possible locations for GD 165B. The circle at higher temperature uses the temperature estimated from the fits in Fig. 3. The circle at lower temperature uses the estimate given in Zuckerman & Becklin (1992). (The luminosity estimate quoted in Zuckerman & Becklin is adopted for both.) Note that the two points place GD 165B at the end of the main sequence near a mass of 0.08 $M_{\odot}$, the dividing line between stars and brown dwarfs.

tions are able to reproduce spectra such as this one. This requires accurate identifications of presumably new molecular absorption species. Furthermore, the bolometric luminosity can be determined only once the spectrum is obtained at longer wavelengths, where the object emits most of its radiation. Both problems can be addressed by acquiring high-quality spectra of GD 165B throughout the infrared.

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