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# IDENTIFYING YOUNG BROWN DWARFS USING GRAVITY-SENSITIVE SPECTRAL FEATURES

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## ABSTRACT

We report the initial results of the Brown Dwarf Spectroscopic Survey Gravity Project to study gravity sensitive features as indicators of youth in brown dwarfs. Low-resolution ($R \sim 2000$) *J*-band and optical ($R \sim 1000$) observations using NIRSPEC and LRIS at the W. M. Keck Observatory reveal transitions of TiO, VO, K I, Na I, Cs I, Rb I, CaH, and FeH. By comparing these features in late-type giants and in old field dwarfs, we show that they are sensitive to the gravity ($g = GM/R^2$) of the object. Using low-gravity spectral signatures as age indicators, we observed and analyzed *J*-band and optical spectra of two young brown dwarfs, G196-3B (20–300 Myr) and KPNO Tau 4 (1–2 Myr) and two possible low-mass brown dwarfs in the $\sigma$ Orionis cluster (3–7 Myr). We report the identification of the $\phi$ bands of TiO near 1.24 $\mu$m and the A-X band of VO near 1.18 $\mu$m together with extremely weak *J*-band lines of K I in KPNO Tau 4. This is the first detection of TiO and VO in the *J* band in a substellar-mass object. The optical spectrum of KPNO Tau 4 exhibits weak K I and Na I lines, weak absorption by CaH, and strong VO bands, also signatures of a lower gravity atmosphere. G196-3B shows absorption features in both wavelength regions, like those of KPNO Tau 4, suggesting that its age and mass are at the lower end of published estimates. Whereas $\sigma$ Ori 51 appears to be consistent with a young substellar object, $\sigma$ Ori 47 shows signatures of high gravity most closely resembling an old L1.5/ L0 and cannot be a member of the $\sigma$ Orionis cluster.

*Subject headings:* infrared: stars — stars: low-mass, brown dwarfs — surveys — techniques: spectroscopic

## 1. INTRODUCTION

Theoretical models predict that substellar objects are much more luminous and hotter when very young (Burrows et al. 2001). Consequently, deep imaging surveys of young clusters can yield very low mass substellar objects that will be too faint to study once they have aged, unless they are located extremely close to the Sun. Hence, the very low end of the initial mass function can be more effectively probed in young clusters. Several groups have reported deep infrared surveys of young star-forming regions at distances ranging from 140 to 450 pc (Luhman et al. 1998, 2000; Luhmann & Rieke 1999; Luhmann 1999, 2000b; Béjar et al. 1999; Stauffer et al. 1999; Ardila et al. 2000; Lucas & Roche 2000; Zapatero Osorio et al. 2000; Mainzer & McLean 2003, among others). For example, in the $\sigma$ Orionis open cluster ($4.2^{+2.7}_{-1.5}$ Myr, Oliveira et al. 2002; $352^{+166}_{-85}$ pc, *Hipparcos*), Zapatero Osorio et al. (2000) report several substellar mass objects which, if members of the association, would have masses in the range 8–15 $M_{\rm Jupiter}$.

One way to distinguish between young and old brown dwarfs is to look for gravity-sensitive spectral features. The radius of field brown dwarfs varies only slightly with mass and age, and therefore the surface gravity ($g = GM/R^2$) is determined by the mass ($\log g \sim 5$). At a young evolutionary stage, however, lower mass objects will have effective temperatures corresponding to those of late M or early L dwarfs. Furthermore, the radius of these young objects can be as much as 3 times greater than their eventual equilibrium state (Burrows et al. 2001). As a result, young objects can exhibit significantly lower surface gravities (10–100 times) than the more massive evolved dwarfs of the same spectral type. Martín et al. (1996) and Luhman et al. (1997) demonstrated that CaH, K I, Na I, and VO features can be used as gravity-sensitive diagnostics in the optical spectra of brown dwarf candidates. Gorlova et al. (2003) showed that the neutral potassium (K I) lines in the *J* band are also sensitive to surface gravity.

In this paper, we present the first results from our survey that focus on young brown dwarfs and their surface gravity spectral indicators. We show that for ages $\lesssim$5 Myr, not only are the K I lines and the FeH feature in the *J* band very weak for a given spectral type, but also infrared TiO and VO bands, normally not present at the boundary between M and L dwarfs in the old field population, are present for the lowest mass objects. We also reveal that the optical spectra of very young brown dwarfs exhibit weaker lines of K I, Na I, Rb I, and Cs I, weaker bands of CaH, and stronger bands of VO than field dwarfs of the same spectral class. These results and the extensive spectral database of old field M, L (Kirkpatrick et al. 1999), and T (Burgasser et al. 2002) dwarfs in the Brown Dwarf Spectroscopic Survey (BDSS; McLean et al. 2003, hereafter M03) and the Kirkpatrick L Dwarf Archive[4] enable us to test the membership of potential very low mass brown dwarfs in young clusters. We have applied these criteria to KPNO Tau 4 in the Taurus-Auriga region (Kenyon et al. 1994b; Briceño et al. 2002), G196-3B (Rebolo et al. 1998), and $\sigma$ Ori 47 and $\sigma$ Ori 51 in the $\sigma$ Orionis open cluster (Béjar et al. 1999; Zapatero Osorio et al. 2000). In § 2, we describe the observations and methods. Results are presented and discussed in § 3, and our conclusions are summarized in § 4.

## 2. OBSERVATIONS AND RESULTS

The objects observed and their relevant photometric properties are listed in Table 1. KPNO Tau 4 was discovered by

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[4] Go to http://spider.ipac.caltech.edu/staff/davy/ARCHIVE/.

TABLE 1
Observing Log and Properties of Sources

| Object | Spectral Type | R.A. (J2000.0) | Decl. (J2000.0) | $I$ (mag) | $J$ (mag) | UT Date Optical Obs. | UT Date NIR Obs. | References |
|---|---|---|---|---|---|---|---|---|
| $\sigma$ Ori 47 ........... | L1.5/L0 V | 05 38 14.5 | −02 40 16 | 20.5 | 17.53 | 2003 Jan 03 | 2003 Mar 24 | 1, 2, 9 |
| $\sigma$ Ori 51 ........... | M9 V | 05 39 03.2 | −02 30 20 | 20.7 | 17.21 | 2003 Jan 02 | 2002 Dec 24 | 3 |
| KPNO Tau 4..... | M9.5 V | 04 27 28.0 | +26 12 05 | 18.7 | 15.00 | 2003 Jan 03 | 2002 Dec 24 | 4, 9 |
| G196-3B........... | L2 V | 10 04 20.7 | +50 23 00 | 18.3 | 14.90 | 1999 Mar 04/05 | 2001 Mar 06 | 5, 6, 9 |
| | . . . | . . . | . . . | . . . | . . . | 2001 Feb 19 | . . . | . . . |
| IO Vir............... | M9.5 III+ | 14 11 17.5 | −07 44 50 | 12.1 | 6.65 | 2003 Jan 03 | 2003 Mar 24 | 7, 8, 9 |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.
References.—(1) Béjar et al. 1999; (2) Zapatero Osorio et al. 1999; (3) Zapatero Osorio et al. 2000; (4) Briceño et al. 2002; (5) Rebolo et al. 1998; (6) Kirkpatrick et al. 2001; (7) Kirkpatrick et al. 1997b; (8) USNO-B1.0 Catalog; (9) 2MASS Catalog.

Briceño et al. (2002) as part of an $I$ and $z'$ deep survey of 8 deg$^2$ in the Taurus-Auriga dark cloud complex (1–2 Myr, 140 $\pm$ 10 pc; Kenyon et al. 1994a). An optical spectrum obtained by the authors was used to assign a spectral type of M9.5 $\pm$ 0.5.G196-3B was discovered by Rebolo et al. (1998) from a direct-imaging search around young, nearby, cool dwarf stars. Its age was estimated at 20–300 Myr based on the chromospheric and coronal properties of G196-3A. Optical spectra indicate G196-3B is an L2 dwarf with a mass estimated at $25^{+15}_{-10}\ M_{\rm Jupiter}$ (Rebolo et al. 1998). $\sigma$ Ori 47 was first reported as a substellar candidate member of the $\sigma$ Orionis cluster (Béjar et al. 1999) as part of a deep $RIz$ survey in an 870 arcminute$^2$ field around the O9.5 V star $\sigma$ Orionis. Follow-up infrared photometry and optical spectroscopy acquired by Zapatero Osorio et al. (1999) suggested a substellar nature of $\sigma$ Ori 47. Zapatero Osorio et al. presented a Keck LRIS spectrum of this object and concluded that the strengths of the hydride and alkali lines are lower than in a field L dwarf of the same type. This would indicate lower gravity and hence a young age for $\sigma$ Ori 47. They also claimed a lithium detection of 4.3 $\pm$ 0.5 Å EW, another indication of youth. A spectral type of L1.5 $\pm$ 0.5 was assigned based on the optical spectrum. $\sigma$ Ori 51 (Zapatero Osorio et al. 2000) was discovered during a deeper follow-up survey of the initial Béjar et al. (1999) sample. Substellar status was determined from fits of the color data to model isochrones for young brown dwarfs. Subsequent low-resolution optical spectroscopy was conducted by Barrado y Navascués et al. (2001), who determined its spectral type to be M9.0 $\pm$ 0.5. Finally, and most importantly, we observed the Mira variable IO Virginis (M9.5 III+) as a template for very low gravities (log $g \sim 0$).

Near-infrared (near-IR) observations were made with NIRSPEC on the Keck II telescope, using a 0$''$.43 slit to yield a resolution of $R = \lambda/\Delta\lambda \sim 2000$ at $J$ band (1.14–1.36 $\mu$m). The $J$ band was chosen because it contains four strong lines of neutral potassium, FeH bands, and a strong $H_2O$ band useful for spectral classification (M03). A detailed description of NIRSPEC is given elsewhere (McLean et al. 1998, 2000). Observations were made as a sequence of nodded pairs by positioning the object at two locations along the slit separated by $\sim$20$''$. Each exposure was 300 s, and at least two nodded pairs were obtained for each source, giving total integration times of 20–60 minutes. The typical signal-to-noise ratio per resolution element for these observations is 20–30, with the exception of $\sigma$ Ori 51, which has a signal-to-noise ratio of $\sim$10. Data extraction and reduction techniques were carried out using REDSPEC, the NIRSPEC reduction package (see M03 for details).

Optical spectra were obtained at the Keck I telescope using the Low-Resolution Imaging Spectrograph (LRIS; Oke et al. 1995). For most of the observations listed in Table 1, the setup and reduction procedures were identical to those discussed in Kirkpatrick et al. (1999). The only exception is the spectrum of G196-3B, which is pieced together from two different LRIS setups. The first setup was used on 1999 March 4/5, resulting in an 9 Å resolution spectrum of G196-3B from 6300 to 10000 Å. On 2001 February 19, we used the 300 lines mm$^{-1}$ grating blazed at 5000 Å to cover the interval from 3800 to 8500 Å. Reductions were identical, and the resulting spectrum has a slightly lower resolution of 11 Å. Because the blue spectrum was taken in better sky conditions, we have constructed a 6300–10,000 Å spectrum for G196-3B by combining both data sets: 1999 March data for $\lambda > 8500$ Å and 2001 February data for $\lambda < 8500$ Å. Spectra obtained on 2003 January 2/3 and 2001 February 19 have been corrected for telluric absorption. This was accomplished by observing a G0 dwarf at similar air mass shortly before or after the target observation and interpolating the continuum across the telluric bands to determine the correction.

## 3. DISCUSSION

Figure 1 shows the NIRSPEC $J$-band spectrum of IO Vir compared with that of KPNO Tau 4 and G196-3B. A remarkable feature in the $J$-band spectra is the appearance of a broad absorption band near 1.24 $\mu$m in both the Mira variable IO Vir and the young M9.5 dwarf KPNO Tau 4. These bands are probably not the result of FeH, as related features at 1.20 $\mu$m are very weak or absent. We instead identify these features as the $\phi$ ($\Delta\nu = -1$) band heads of TiO (Galehouse et al. 1980). A second feature near 1.18 $\mu$m is attributed to the A–X ($\Delta\nu = -1$) band of VO (Cheung et al. 1982). These oxide bands are common in the late type $J$-band spectra of Mira variables (Hinkle et al. 1989; Joyce et al. 1998) and apparently also present in the low-gravity atmospheres of young brown dwarfs. The K I doublets (1.168, 1.177 $\mu$m and 1.243, 1.254 $\mu$m) are absent in the cool, low-gravity atmosphere of IO Vir and only weakly present in the spectrum of KPNO Tau 4, consistent with the behavior noted by Gorlova et al. (2003). The $H_2O$ band at 1.34 $\mu$m in KPNO Tau 4 is deeper than expected for an M9.5 object, being more consistent with a L2 dwarf (M03). This effect could likely be the result of the $H_2O$ band showing some slight sensitivity to gravity, as is the case in giant star atmospheres, but the effect is much less noticeable than for the K I lines. The spectrum of the L2 dwarf G196-3B exhibits similar features. The deep absorption in the range 1.14–1.20 $\mu$m can be attributed to a mixture of VO, TiO, and possibly $H_2O$. We have confirmed the identification of the TiO

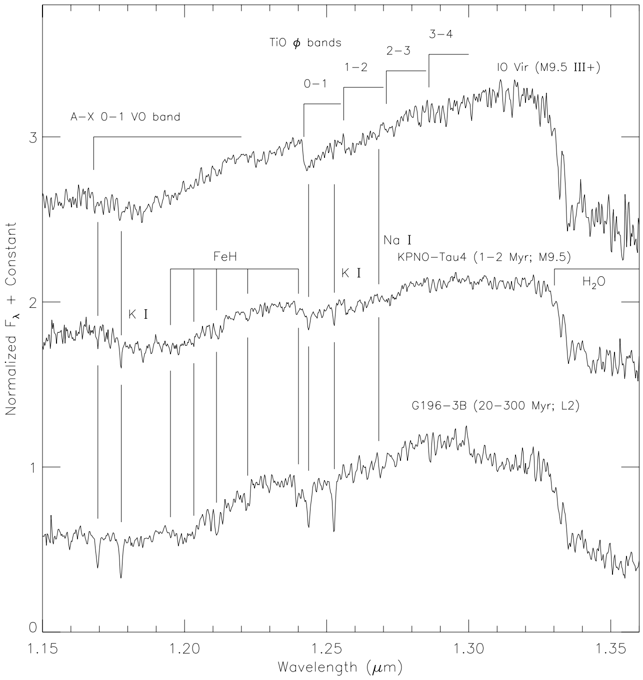


FIG. 1.—NIRSPEC *J*-band spectra of the young, low-mass brown dwarfs KPNO-Tau 4 and G196-3B are plotted together with the late M giant IO Vir. The spectrum of IO Vir shows absorption bands of VO and TiO located at 1.18 and 1.24–1.28 $\mu$m, respectively. Similar features appear in the spectrum of KPNO-Tau 4 and G196-3B, suggesting that they have low-gravity atmospheres. Spectral types listed here are based on optical classifications. Spectra are normalized at 1.265 $\mu$m and separated from one another vertically by integer offsets.

and VO bands by observing these objects at shorter wavelengths (*z* band), where the fundamental transitions ($\Delta\nu = 0$) are easily detected. We conclude that the presence of TiO and VO, weak K I lines, and weak FeH absorption in the near-IR spectra of KPNO Tau 4 and G196-3B are indicative of low surface gravity and hence support their identification as young, low-mass brown dwarfs.

Figure 2 shows LRIS spectra of IO Vir, KPNO Tau 4, 2MASSW J0149090+295613 (hereafter, 2M0149+29; Liebert et al. 1999), G196-3B, and Kelu 1 (Kirkpatrick et al. 1999). The top three spectra show the effects of differing gravity in late M stars. The M giant IO Vir exhibits the hallmarks of low gravity, with very weak or nonexistent absorptions by K I and Na I, weak absorption by CaH, and strong, bowl-shaped depressions by VO. The presumably solar-age field dwarf 2M0149+29 (M9.5 V) shows the hallmarks of higher gravity: strong absorptions by K I and Na I, strong absorption by CaH, and less pronounced features attributable to VO. The spectrum of KPNO Tau 4 shows spectroscopic characteristics intermediate between the field dwarf and the giant (cf. Briceño et al. 2002). Such a gravity signature is expected for a dwarf that is much less massive and/or more extended than a higher mass field counterpart of similar temperature. This result is consistent with KPNO Tau 4 being young.

The bottom two spectra of Figure 2 show the young L2 dwarf G196-3B compared to the presumably older field L2 dwarf Kelu 1. Again, the spectrum of the younger (lower mass) object shows the signatures of lower gravity, most notably the weaker lines of the alkali elements K I, Rb I, Na I, and Cs I. The Li I line shows the opposite effect, as lithium has been largely depleted in the more massive Kelu 1 but is retained in the lower mass brown dwarf G196-3B (Rebolo et al. 1992).

We now consider the $\sigma$ Orionis objects. Based on the near-IR and optical signatures of low gravity established in Figures 1 and 2, the comparison of the *J*-band and optical spectra of $\sigma$ Ori 47 and 51 in Figures 3 and 4, respectively, is revealing. The *J*-band spectrum of $\sigma$ Ori 47 contains strong K I lines, moderate FeH absorption at 1.20 $\mu$m, and relatively deep $H_2O$ absorption at 1.34 $\mu$m. On the other hand, the *J*-band spectrum of $\sigma$ Ori 51 has very weak K I lines and very weak FeH absorption. Although the TiO and VO bands are not detected, the weakness of the K I lines and FeH band in the *J*-band spectrum of $\sigma$ Ori 51 is consistent with it being a lower gravity object. A comparison of the $H_2O$ absorption band at 1.34 $\mu$m to the BDSS sample (M03) shows that the depth of this band matches most closely with an L0–L1 dwarf for $\sigma$ Ori 51. Again, a slightly later IR spectral type suggests that, at our resolution of $R \sim 2000$, we could likely be detecting some sensitivity of the $H_2O$ band to gravity. The absence of the *J*-band TiO and VO bands in $\sigma$ Ori 51 may be attributed to its somewhat higher surface gravity as compared to KPNO Tau 4 because of its older age ($\sim$5 Myr compared to $\sim$1 Myr) and warmer atmosphere, although veiling is a viable alternative hypothesis. The strength of the near-IR spectral features observed in $\sigma$ Ori 47 are consistent with the known field dwarf 2MASS 0345+35 (L0; Kirkpatrick et al. 1997a) plotted at the top of Figure 3 for comparison. Based on the equivalent width of the K I lines and the strength of the $H_2O$ band at 1.34 $\mu$m, the near-IR data support the conclusion that $\sigma$ Ori 47 appears to be a much older L0$\pm$0.5 dwarf.

Figure 4 shows LRIS spectra for these objects. A comparison of the spectrum of $\sigma$ Ori 51 to the M star spectra in Figure 2 confirms that it has the signatures of lower gravity, most notably weak Na I, bowl-shaped depressions by VO, and weak CaH, demonstrating that it is a young object. For $\sigma$ Ori 47, we find that the opposite is true, in contradiction to the claims of Zapatero Osorio et al. (1999). Inset A in Figure 4 shows a comparison of the spectra of G196-3B (from Fig. 2) and $\sigma$ Ori 47 in the region around the 6708 Å Li I line. We find no lithium line down to 2 Å EW (Li I in G196-3B has EW = 6 Å). Inset B shows a comparison of $\sigma$ Ori 47 to the low-gravity dwarf G196-3B and to the presumably high-gravity L1.5 V field dwarf 2MASSW J0832045−012835 (hereafter, 2M0832−01; Kirkpatrick et al. 2000) in the region

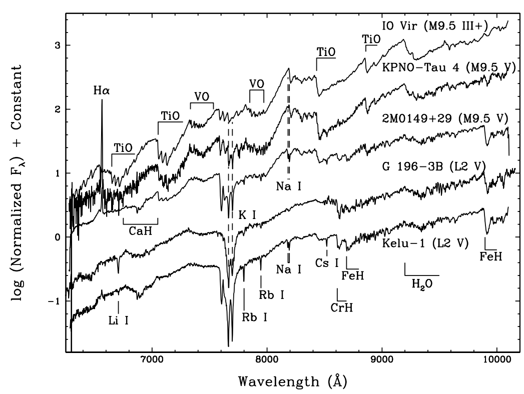


FIG. 2.—LRIS optical spectra of three M9.5 objects (*top*) and two early L dwarfs (*bottom*). Noteworthy spectral features are labeled. As noted in the text, the telluric A bands (6867–7000 Å) and B bands (7594–7685 Å) of $O_2$ are evident in the spectra of 2M0149+29 and Kelu-1 but have been corrected in the other spectra. Note the differences in feature strengths in the M9.5 spectra from the low-gravity giant IO Vir down to the high-gravity field dwarf 2M0149+29, and between the lower gravity, young L dwarf G196-3B and the higher gravity, field L dwarf Kelu-1. See text for more details.

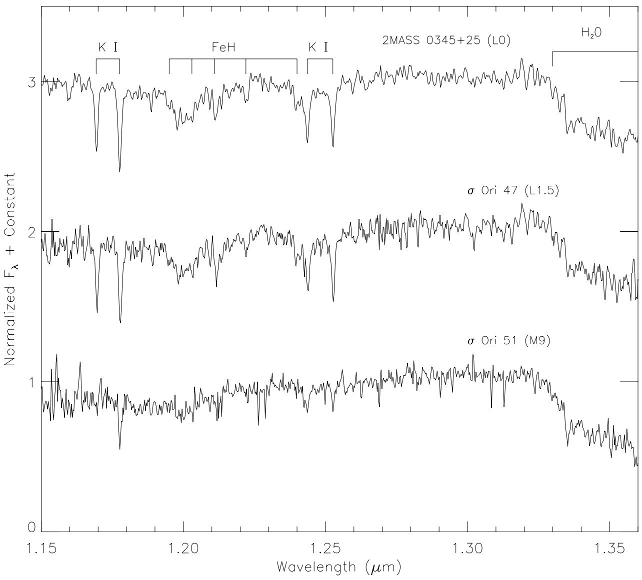


Fig. 3.—NIRSPEC *J*-band spectra of 2MASS 0345+25, $\sigma$ Ori 47, and $\sigma$ Ori 51. 2MASS 0345+25 is plotted for comparison as a known higher gravity object. $\sigma$ Ori 51 exhibits very weak K I lines and weak FeH absorption, consistent with a low surface gravity, whereas $\sigma$ Ori 47 has relatively strong absorption features at these locations and, at these wavelengths, matches a field L0 dwarf most closely. Spectral types listed here are based on optical classifications. Spectra are normalized at 1.265 $\mu$m and separated from one another vertically by integer offsets.

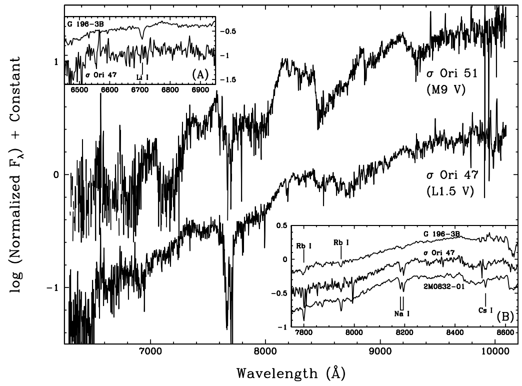


Fig. 4.—LRIS optical spectra of two candidate members of the $\sigma$ Orionis cluster. Both spectra have been corrected for telluric absorption and feature identifications can be found in Fig. 2. Comparison to the spectra in Fig. 2 further shows that $\sigma$ Ori 51 is a low-gravity object and $\sigma$ Ori 47 is not. This latter point is further demonstrated in insets A and B. Inset A illustrates no obvious Li I absorption line, as the comparison to the low-gravity spectrum of G196-3B (L2 V) shows. Inset B shows that the alkali line strengths of $\sigma$ Ori 47 are similar to the field dwarf 2M0832-01 (L1.5 V) but quite unlike the alkali strengths in the young G196-3B. See text for more details.

near the other alkali lines. The $\sigma$ Ori 47 spectrum shows a strong Na I doublet at 8183 and 8195 Å like that of a field L dwarf. Fortunately, this Na I doublet falls in a region with very little contamination by telluric OH emission, so the spectrum here is less noisy. Even in the wavelength regions where residual OH emission causes more of a problem, such as near the Rb I and Cs I lines at 7800, 7948, and 8521 Å, absorptions by the alkali elements are obvious and of comparable strength to the absorptions in a field L dwarf.

We classify $\sigma$ Ori 47 in the optical as an L1.5, the same spectral type assigned to 2M0832−01, and suggest that within the uncertainties, the two spectra are identical. Hence, $\sigma$ Ori 47 appears to be an old, high-mass, field L dwarf. The L1.5 optical spectral type and 2MASS *J* magnitude of 17.53 $\pm$ 0.24 suggest a distance of 120 pc (see eq. [1] from Kirkpatrick et al. 2000), roughly a factor of 3 closer than the cluster itself. The higher gravity implies an age closer to that of the Sun, which means the mass of this L dwarf is near the stellar/substellar break of 0.075–0.080 $M_\odot$ (Burrows et al. 1997). We conclude that this object shows no signs of youth, is unassociated with the cluster, and is not an object "reaching the mass boundary between brown dwarfs and giant planets" near 0.015 $M_\odot$, as originally reported (Zapatero Osorio et al. 1999).

## 4. CONCLUSIONS

The identification of gravity-sensitive spectral features is a powerful technique in the study of brown dwarfs. By comparison with a known object of lower surface gravity ($\log g \sim 0$), several indicators of low gravity in brown dwarfs have been identified. We have shown empirically that in the *J* band, the $\phi$ ($\Delta\nu = -1$) band heads of TiO and the A–X ($\Delta\nu = -1$) band of VO appear in very young late-type M or early L objects as a result of low surface gravity. This is the first detection of these bands in a substellar object. In slightly older brown dwarfs, weak FeH and K I features indicate low gravity. Absorption from $H_2O$ in the *J* band is slightly greater than expected for the given spectral type. In optical spectra, weak alkali lines of Na I, K I, Rb I, and Cs I, but strong Li I absorption, together with weak CaH and strong VO absorption, are indicative of low gravity. Older late-M and early-L dwarfs with higher surface gravity always exhibit strong alkali lines in both the visible and near-IR, strong FeH in the *J* band, and strong CaH around 7000 Å. For KPNO Tau 4 and $\sigma$ Ori 51, we find optical and infrared spectral features consistent with low gravity and youth, a necessary condition for membership in a young cluster. G196-3B is also confirmed as a young brown dwarf, consistent with it being coeval with its more massive companion. $\sigma$ Ori 47 however, does not exhibit any of the features of low surface gravity, and we conclude that it is not young and therefore not a low-mass member of the $\sigma$ Orionis cluster, but instead an early-L field dwarf with a mass near the stellar/substellar boundary.

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