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EVIDENCE OF CLOUD DISRUPTION IN THE L/T DWARF TRANSITION

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ABSTRACT

Clouds of metal-bearing condensates play a critical role in shaping the emergent spectral energy distributions of the coolest classes of low-mass stars and brown dwarfs, L and T dwarfs. Because condensate clouds in planetary atmospheres show distinct horizontal structure, we have explored a model for partly cloudy atmospheres in brown dwarfs. Our model successfully reproduces the colors and magnitudes of both L and T dwarfs for the first time, including the unexpected brightening of the early- and mid-type T dwarfs at the *J* band, provided that clouds are rapidly removed from the photosphere at $T_{eff} \approx 1200$ K. The clearing of cloud layers also explains the surprising persistence and strengthening of gaseous FeH bands in early- and mid-type T dwarfs. The breakup of cloud layers is likely driven by convection in the troposphere, analogous to phenomena observed on Jupiter. Our results demonstrate that planetary-like atmospheric dynamics must be considered when examining the evolution of free-floating brown dwarfs.

Subject headings: infrared: stars — stars: atmospheres — stars: fundamental parameters — stars: individual (SDSS J1254−0122, 2MASS J0559−1404) — stars: low-mass, brown dwarfs

On-line material: color figure

1. INTRODUCTION

The recent discovery of a vast population of free-floating brown dwarfs in the vicinity of the Sun (Kirkpatrick et al. 1999, 2000; Martín et al. 1999; Burgasser et al. 2002a; Geballe et al. 2002) has led to the definition of two new spectroscopic classes, L dwarfs and T dwarfs. These are the first additions to the standard stellar sequence in over 60 years, encompassing objects cooler than the M spectral class. L dwarfs (Kirkpatrick et al. 1999; Martín et al. 1999) are characterized by absorption bands of metal hydrides (e.g., FeH, CrH, and MgH), strong alkali lines (Li, Na, K, Rb, and Cs), and H_2O and CO absorption in the near-infrared. Below effective temperatures $T_{eff} \sim 1500$ K, CO reduces to CH_4 (Fegley & Lodders 1996), a molecule that has distinct absorption bands at 1.6 and 2.2 μm. Objects exhibiting these CH_4 features have grossly different spectroscopic and photometric properties as compared with L dwarfs, and they are designated T dwarfs (Kirkpatrick et al. 1999, 2000; Burgasser et al. 2002a). The spectroscopic sequence M to L to T is the evolutionary cooling sequence for a typical brown dwarf.

L dwarfs are further characterized by the presence of condensates near or just below their photospheres. These condensates include liquid iron; solid VO; and aluminum, calcium, magnesium, and titanium-bearing minerals such as enstatite ($MgSiO_3$), grossite ($CaAl_4O_7$), and perovskite ($CaTiO_3$) (Burrows & Sharp 1999; Lodders 1999). The opacity of the condensate grains and droplets gives L dwarfs fairly red near-infrared colors, with $J-K_s \sim 2$ (Kirkpatrick et al. 2000). Conversely, condensates in mid- and late-type T dwarfs appear to lie deep below the photosphere. These objects have neutral near-infrared colors, $J-K_s \sim 0$, governed by strong absorption features of H_2O, CH_4, and collision-induced H_2, particularly at the *K* band (Burgasser et al. 2002a).

Three classes of models have been developed to account for condensates in brown dwarf atmospheres. The dusty model (Lunine et al. 1989; Chabrier et al. 2000; Allard et al. 2001) assumes that condensates remain dispersed in the gas and in chemical equilibrium throughout the atmosphere. The clear model (Burrows et al. 1997) removes all condensates from the photosphere as they form, presumably through gravitational settling. The cloudy model (Ackerman & Marley 2001; Marley et al. 2002) incorporates condensate cloud formation based on an assumed sedimentation efficiency, f_{rain}. The dusty and clear models are extreme cases of the cloudy model with very low and very high values of f_{rain}, respectively.

In this Letter, we present an exploratory model of partial cloud clearing in cool dwarf atmospheres derived from the cloudy and clear models. In § 2, we describe our model and compare its derived photometry with the near-infrared color-magnitude diagram of late-type dwarfs. This analysis indicates that a rapid clearing of clouds takes place across the L/T transition. In § 3, we present further evidence of cloud clearing in the persistence and strengthening of FeH absorption at 9896 Å in the early- and mid-type T dwarfs. We discuss our results in § 4.

2. PHOTOMETRIC EVIDENCE OF CLOUD CLEARING

2.1. *The Color-Magnitude Diagram for Late-Type Dwarfs*

Figure 1 shows the near-infrared color-magnitude diagram for a sample of M, L, and T dwarfs with known parallaxes. Photometry was obtained from the Two Micron All Sky Survey (2MASS; Skrutskie et al. 1997), and parallaxes were obtained

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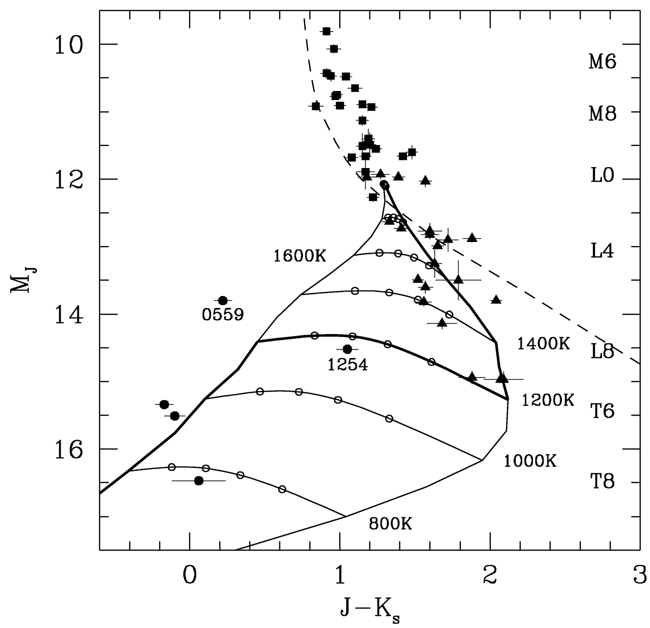

FIG. 1.—Near-infrared color-magnitude diagram of M, L, and T dwarfs. The absolute J magnitudes and $J-K_s$ infrared colors are shown for a sample of M (*squares*), L (*triangles*), and T (*filled circles*) dwarfs with known parallaxes. The positions of 2MASS J0559−1404 and SDSS J1254−0122 are indicated. The predicted colors and magnitudes for the dusty (*dashed line*), clear (*left solid line*), and cloudy (*right solid line*; $f_{\rm rain} = 3$) atmosphere models are plotted as a function of $T_{\rm eff}$ at constant gravity, $g = 10^5$ cm s^{-2} (typical for very low mass main-sequence stars and evolved brown dwarfs). Connecting the cloudy and clear tracks are the predicted fluxes for our partly cloudy models at $T_{\rm eff}$ = 800, 1000, 1200, 1400, 1600, and 1800 K. The open circles indicate the cloud coverage fraction in steps of 20%. The apparent evolutionary track of brown dwarfs based on the empirical data is indicated by the thickened line, which crosses from the cloudy to clear track at $T_{\rm eff} \approx 1200$ K. [*See the electronic edition of the Journal for a color version of this figure.*]

from the USNO Parallax Program (Dahn et al. 2002) or from *Hipparcos* (Perryman et al. 1997) in the case of companions to nearby stars. As described in Dahn et al. (2002), late-type M and L dwarfs are increasingly redder and fainter toward later spectral types, but the transition to the bluer T dwarfs is marked by a distinct brightening at the J band, with both the T2 dwarf SDSS J1254−0122 (Leggett et al. 2000) and the T5 dwarf 2MASS J0559−1404[8] (Burgasser et al. 2000) being brighter at the J band than the latest type L dwarfs. Note that neither of these objects is expected to be young and hence less compact ($R \gtrsim 1\ R_{\rm J}$; Burrows et al. 1997) based on extremely weak or absent Hα emission (Burgasser et al. 2002b; J. D. Kirkpatrick et al. 2002, in preparation). Late-type T dwarfs are increasingly bluer in $J-K_s$ color and fainter at the J band.

Also shown in this figure are color-magnitude tracks for the three atmosphere models described above. The dusty model (Chabrier et al. 2000; *dashed line*) reproduces the colors of early-type L dwarfs but continues to redden to colors far greater than those observed for the mid- and late-type L dwarfs. This is due to the continued influence of dust opacity, which mutes the otherwise strong absorption bands of H_2O, CH_4, and H_2. The clear model (*left solid line*) reproduces the colors of mid- and late-type T dwarfs, but not those of L dwarfs. Finally, the cloudy model (*right solid line*) successfully reproduces the near-infrared color limit for the latest type L dwarfs, $J-K_s \lesssim 2$–2.5 (Kirkpatrick et al. 2000; Marley et al. 2002) and subsequently turns to bluer near-infrared colors. However, the predicted transition occurs over a greater decrease in brightness, ΔM_J = 2–3 mag from $J-K_s = 2$ to $J-K_s = 0$, than is observed. Increasing $f_{\rm rain}$ in this model (i.e., moving toward a more cleared photosphere) allows the color transition to occur at brighter magnitudes but fails to match the colors and magnitudes of the latest L dwarfs. Therefore, the condensate cloud model, while adequately reproducing the brightness and color evolution of L dwarfs, cannot reproduce the observed rapid transition to the T dwarfs.

Is it possible to resolve this apparent discrepancy between the cloudy model and the observations? All three atmosphere models assume horizontal homogeneity and therefore uniform condensate distribution over the visible disk of the brown dwarf. However, clouds in the planets of the solar system, for instance, Jupiter's upper cloud decks of solid NH_3 and NH_4SH, display discrete structures of spots and bands caused by tropospheric weather patterns. Breaks between the clouds on Jupiter coincide with bright "hot spots" at 5 μm (Westphal, Matthews, & Terrile 1974), as light emerges from warmer regions well below the upper cloud decks. Since horizontally nonhomogeneous clouds are ubiquitous in planetary atmospheres, it is reasonable to expect that similar features could be present in the condensate cloud layers of brown dwarfs as well (Ackerman & Marley 2001).

2.2. *Cloud Clearing Model*

Connecting the cloudy and clear tracks in Figure 1 are the predicted fluxes for an alternative model we have developed that allows for partial clearing of condensate clouds. These were constructed by first linearly interpolating between the fluxes of the clear model and a modified cloudy model in which the cloud opacity has been removed, weighing by the fraction of cloud coverage. This combination approximates the effect of partial cloud opacity on the underlying atmospheric pressure-temperature profile. We then linearly interpolated the resulting fluxes with those of the standard cloudy model, again weighing by the fractional cloud coverage, to derive the relative brightness contributions of cloudy and cloud-free regions. Our simple approach assumes that many clouds are distributed randomly across the observed disk.

When compared with the data, we see that the evolution from the red and dusty L dwarfs to the blue and clear T dwarfs can be traced (Fig. 1, *thick line*) down the cloudy track to an effective temperature $T_{\rm eff} \approx 1200$ K, across the 1200 K partly cloudy model, and subsequently down the cloud-free track. SDSS J1254−0122 is a true transition object, lying close to the 1200 K partly cloudy track at roughly 40% cloud coverage. However, 2MASS J0559−1404 appears to have a cloud-free photosphere. The $T_{\rm eff}$ at which the color transition appears to take place is only slightly cooler than that estimated for one of the latest type L dwarfs, Gliese 584C ($T_{\rm eff}$ = 1350 K; Kirkpatrick et al. 2000; Dahn et al. 2002). The clearing of clouds at nearly constant $T_{\rm eff}$ explains the apparent brightening of the early-type T dwarfs at 1 μm, as the emitting layers below the clouds in these objects would be warmer than the layers above the cloud decks in late-type L dwarfs. Note that there is some intrinsic scatter among the empirical data, likely due to the influence of gravity, rotation, and metallicity on cloud cover-

[8] Burgasser (2001) has suggested that 2MASS J0559−1404 may be an unresolved binary brown dwarf. However, even if it were an equal-magnitude double, it would still remain brighter at the J band than the latest L dwarfs.

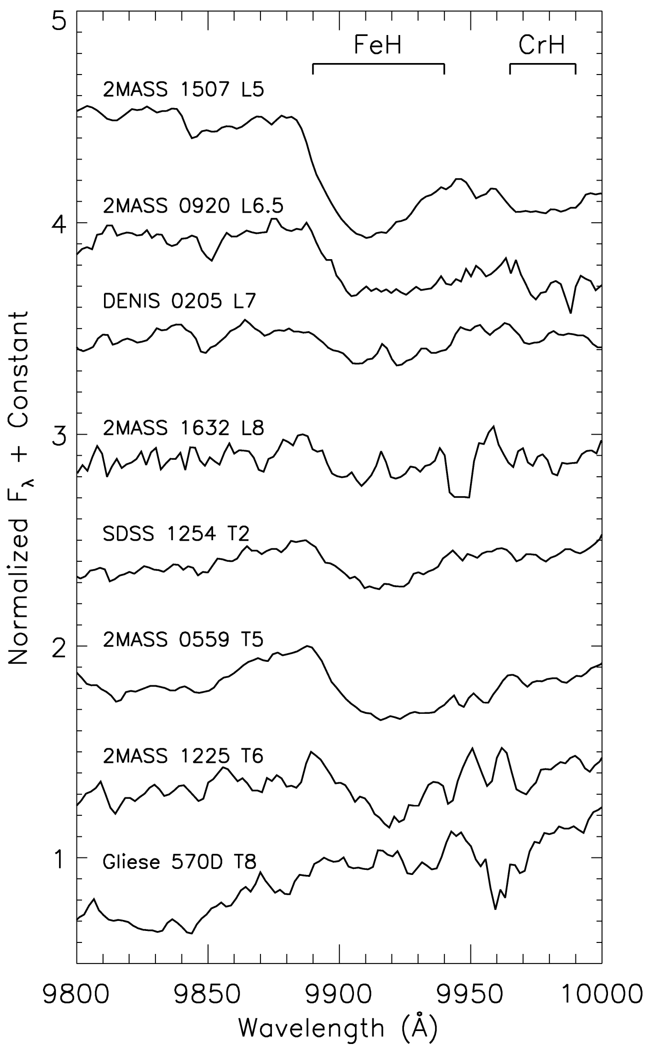

FIG. 2.—Evolution of FeH with spectral type. The optical spectra of four late L dwarfs (L5 2MASS J1507−1627, L6.5 2MASS J0920+3517, L7 DENIS J0205−1159, and L8 2MASS J1632+1904) and four T dwarfs (T2 SDSS J1254−0122, T5 2MASS J0559−1404, T6 2MASS J1225−2739, and T8 Gliese 570D) are shown in the 9800-10000 Å regime. Spectral types are from Kirkpatrick et al. (1999, 2000) and Burgasser et al. (2002a). Spectra are normalized at 9870 Å and offset for clarity. The 9896 Å FeH and 9969 Å CrH bands are indicated. The FeH band rapidly fades from L5 to L8 but appears to recover and strengthen toward T5, disappearing again in the coolest T dwarfs.

age.[9] Nonetheless, the apparently sudden color transition from L to T clearly cannot be explained by the progressive sinking of a uniform cloud deck with decreasing $T_{\rm eff}$ but is possible through the disruption of condensate clouds.

3. SPECTROSCOPIC EVIDENCE OF CLOUD CLEARING: FeH ABSORPTION

There is additional evidence that light emitted at 1 μm by early- and mid-type T dwarfs is seen through opening holes in

[9] Magnetic activity may also be a source of photometric scatter. Magnetically active low-mass dwarfs have extended cool spots (Alekseev & Gershberg 1997) that could exhibit stronger H_2O and/or CH_4 absorption features, resulting in later type spectral morphologies and photometric colors for a given $T_{\rm eff}$. This phenomenon would not explain the rapid L/T transition, however, again because of the lack of strong Hα emission in either SDSS J1254−0122 or 2MASS J0559−1404, as well as the very low photospheric magnetic Reynolds numbers in these cool, neutral atmospheres (Gelino et al. 2002).

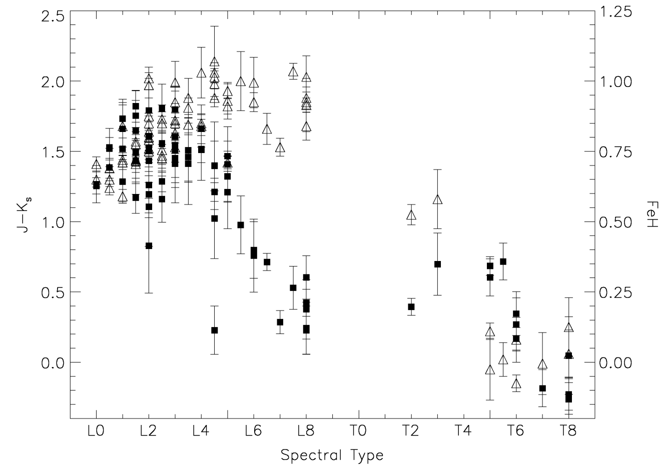

FIG. 3.—FeH band strengths and near-infrared colors as a function of spectral type. The filled squares plot the 9896 Å FeH band index (Kirkpatrick et al. 1999) of L and T dwarfs measured from optical spectra, while the open triangles plot their 2MASS $J-K_s$ colors. The spectral types are from Kirkpatrick et al. (1999, 2000) and Burgasser et al. (2002a). The FeH band weakens rapidly from the mid- to late-type L dwarfs, where $J-K_s$ becomes slightly redder before leveling off at $J-K_s \sim 2$. Instead of disappearing, however, the FeH band persists through T5.5, with some objects showing slightly stronger FeH absorption than the latest L dwarfs.

condensate cloud decks. Figure 2 plots the optical spectra of a series of late-type L and T dwarfs (Kirkpatrick et al. 1999, 2000; A. J. Burgasser et al. 2002, in preparation), obtained using the Low Resolution Imaging Spectrograph (Oke et al. 1995) on Keck. Spectral types listed are from Kirkpatrick et al. (1999, 2000) and Burgasser et al. (2002a) and are consistent with a monotonic $T_{\rm eff}$ sequence (Burgasser et al. 2002a). Here we focus on the region centered at the 9896 Å FeH band. This feature weakens in the later type L dwarfs, in concert with the observed disappearance of the 8962 Å FeH band (Kirkpatrick et al. 1999). This is consistent with the segregation of liquid iron into condensate clouds, which depletes the atmosphere of iron-bearing gases above the cloud layer. As the clouds settle below the photosphere with decreasing temperature, the amount of detectable FeH drops as well. However, the 9896 Å FeH band unexpectedly reappears in SDSS J1254−0122 and is quite pronounced in 2MASS J0559−1404. The retention of FeH absorption from late-type L dwarfs to early- and mid-type T dwarfs is a general trend, as shown in Figure 3. The FeH band clearly weakens from L4 to L8 but persists and even strengthens slightly toward type T5.5, subsequently weakening in the latest T dwarfs.

The plateau in band strength across the L/T transition cannot be explained with a cloud deck that gradually sinks below the photosphere with decreasing $T_{\rm eff}$. In this case, we would only see the atmosphere above the cloud deck in which FeH is depleted. However, if holes are present in the clouds, deeper and warmer regions in which FeH is not depleted become observable. These deep layers can be detected at 1 μm, where H_2O, CH_4, and H_2 absorption is relatively weak. Since the reappearance of FeH coincides with the turnover in $J-K_s$ color, the hypothesis of cloud clearing simultaneously explains both phenomena.

4. DISCUSSION

The disruption of condensate clouds in brown dwarf atmospheres likely begins when the cloud deck forms within the atmospheric convection zone and becomes subject to coherent vertical motions. At higher effective temperatures, the clouds lie primarily above the radiative-convective boundary and would likely remain spatially uniform, perhaps like the stratospheric hazes on Titan and the giant planets. Evidence of vertical transport has already been seen in cool brown dwarfs, with the detection of CO absorption at 4.7 μm in the T6.5 dwarf Gliese 229B (Nakajima et al. 1995) in excess of its equilibrium abundance (Noll, Geballe, & Marley 1997; Oppenheimer et al. 1998). Photometric studies of late-type L and T dwarfs also indicate far greater absorption in the 5 μm band than predicted by chemical equilibrium models (Leggett et al. 2002; Reid & Cruz 2002), likely caused by enhanced CO abundances brought up by vertical flows. Since the principal cloud decks lie within 0.5 pressure scale heights of one another, the convective motion need not be particularly vigorous to disrupt all layers. Note that upwelling brings substantial CO into the photosphere because of its stable bond and hence relatively slow conversion to CH_4 (Lodders & Fegley 2002). The fragility of the FeH bond (1.63 eV vs. 11.09 eV for CO) precludes any similar nonequilibrium enhancement of this species above the cloud layer.

The picture of a brown dwarf's atmospheric evolution presented here has a number of observable consequences. First, the T_{eff} scale between the late-type L and early-type T dwarfs should be very narrow; this has already been surmised by a number of studies (Kirkpatrick et al. 2000; Burgasser et al. 2002a). A narrow temperature scale also implies fewer early-type T dwarfs than mid- or late-type T dwarfs, given the shorter time a brown dwarf spends in this phase of its thermal evolution. The statistics are currently insufficient to adequately test this prediction. We also expect substantial photometric and/or spectroscopic variability in late-type L and early-type T dwarfs, caused by the formation, evolution, and motion (rotational or wind-driven) of cloud holes in their upper atmospheres. Such weather phenomena have been previously cited to explain nonperiodic variability in late-type M and early-type L dwarfs (Bailer-Jones & Mundt 2001; Martín, Zapatero Osorio, & Lehto 2001). Similar variability could be significant at 1 μm in the L/T transition.

Filling in the color-magnitude sequence of late-type L and early-type T dwarfs will enable us to further characterize the behavior of condensate clouds in brown dwarf atmospheres. Regardless, the observed spectral and photometric properties of brown dwarfs indicate that the planetary-like phenomena of cloud formation and disruption are important in the evolution of free-floating brown dwarfs.

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REFERENCES

Ackerman, A. S., & Marley, M. S. 2001, ApJ, 556, 872
Alekseev, I. Yu., & Gershberg, R. E. 1997, in Stellar Magnetic Fields, ed. Yu. V. Glagolevskij & I. I. Romanyuk (Moscow: Spec. Astrophys. Obs.), 76
Allard, F., Hauschildt, P. H., Alexander, D. R., Tamanai, A., & Schweitzer, A. 2001, ApJ, 556, 357
Bailer-Jones, C. A. L., & Mundt, R. 2001, A&A, 367, 218
Burgasser, A. J. 2001, Ph.D. thesis, Caltech
Burgasser, A. J., et al. 2000, AJ, 120, 1100
———. 2002a, ApJ, 564, 421
Burgasser, A. J., Liebert, J., Kirkpatrick, J. D., & Gizis, J. E. 2002b, AJ, 123, 2744
Burrows, A., et al. 1997, ApJ, 491, 856
Burrows, A., & Sharp, C. M. 1999, ApJ, 512, 843
Chabrier, G., Baraffe, I., Allard, F., & Hauschildt, P. 2000, ApJ, 542, 464
Dahn, C. C., et al. 2002, AJ, submitted
Fegley, B., & Lodders, K. 1996, ApJ, 472, L37
Geballe, T. R., et al. 2002, ApJ, 564, 466
Gelino, C. R., Marley, M. S., Holtzman, J. A., Ackerman, A. S., & Lodders, K. 2002, ApJ, submitted
Kirkpatrick, J. D., et al. 1999, ApJ, 519, 802
———. 2000, AJ, 120, 447
Leggett, S. K., et al. 2000, ApJ, 536, L35
Leggett, S. K., et al. 2002, ApJ, 564, 452
Lodders, K. 1999, ApJ, 519, 793
Lodders, K., & Fegley, B. 2002, Icarus, 155, 393
Lunine, J. I., Hubbard, W. B., Burrows, A., Wang, Y.-P., & Garlow, K. 1989, ApJ, 338, 314
Marley, M. S., Seager, S., Saumon, D., Lodders, K., Ackerman, A. S., Freedman, R. S., & Fan, X. 2002, ApJ, 568, 335
Martín, E. L., Delfosse, X., Basri, G., Goldman, B., Forveille, T., & Zapatero Osorio, M. R. 1999, AJ, 118, 2466
Martín, E. L., & Zapatero Osorio, M. R., & Lehto, H. J. 2001, ApJ, 557, 822
Nakajima, T., Oppenheimer, B. R., Kulkarni, S. R., Golimowski, D. A., Matthews, K., & Durrance, S. T. 1995, Nature, 378, 463
Noll, K. S., Geballe, T. R., & Marley, M. S. 1997, ApJ, 489, L87
Oke, J. B., et al. 1995, PASP, 107, 375
Oppenheimer, B. R., Kulkarni, S. R., Matthews, K., & van Kerkwijk, M. H. 1998, ApJ, 502, 932
Perryman, M. A. C., et al. 1997, A&A, 323, L49
Reid, I. N., & Cruz, K. L. 2002, AJ, 123, 466
Skrutskie, M. F., et al. 1997, in The Impact of Large Scale Near-IR Sky Surveys, ed. F. Garzón et al. (Dordrecht: Kluwer), 25
Westphal, J. A., Matthews, K., & Terrile, R. J. 1974, ApJ, 188, L111