

A Spectroscopic Study of Cool, Field Brown Dwarf Neighbors

Program contacts: James Liebert, H.S. Stockman, R. Michael Rich
Scientific category: EXTRASOLAR PLANETS
Instruments: NIR/SPEC, MIR/SPEC
Days of observation: 0

Abstract

The Sloan Digital Sky Survey (SDSS), Two Micron Sky Survey (2MASS) and Deep Near Infrared Survey (DENIS) have already found many dozens of brown dwarfs in the late 1990s. Many of the new spectral class of L dwarfs show undepleted lithium, which indicates that their deep interiors are not hot enough to fuse protons. Methane or T dwarfs with surface temperatures near 1,000 K have also been found as isolated objects in the solar neighborhood. The predicted luminosity function of substellar objects peaks at still lower temperatures (~ 400 -500 K) where M_K is fainter than 20th, and the above-mentioned surveys are not sensitive. These objects are expected to emit significant radiation in the 3.5–10 μ wavelength range. Spectrophotometric study of these faint entities can be conducted only with the NGST. Study of the atmospheric abundances and line profiles is essential to determine such things as the surface temperature and gravity (mass), rotation rate, amount of dust and cloud formation, mixing and other important atmospheric processes. One also wants to know if they form disks and planets, and exhibit magnetic dynamo activity. The astrophysics of field substellar objects is a new piece of the overall study of planet and star formation processes.

ASWG DRM Proposal
A Spectroscopic Study of Cool, Field Brown Dwarf Neighbors

Observing Summary:

Target	RA	Dec	m_{AB}	Configuration/mode	Days
.13 GL 229B	05 08 28	-21 50 36	K=14.3	N&MIRSPEC R10000	0
.13 2MASSW J1632	16 32 29	+19 04 41	K=13.98	N&MIRSPEC R10000	0
.13 DENIS-P J1228	12 28 12	-15 47 00	K=12.81	N&MIRSPEC R10000	0
.14 J162414	16 24 14	00 00 00	K=17.6	N&MIRSPEC R10000	0
.21 J1217	12 17 11	-03 11 13	K=18.3	N&MIRSPEC R10000	0
.14 J1225	12 25 54	-27 39 47	K=16.9	N&MIRSPEC R10000	0
.18 J1237	12 37 39	+65 26 15	K=18.	N&MIRSPEC R10000	0
.18 J1346	13 46 46	-00 31 50	K=18	N&MIRSPEC R10000	0
.0 COOLER TDS 9-11	180 00 00	+65	K=21	N&MIRSPEC R10000	12
Grand total days					12

NOTE: This grand total (12) does not equal the number (0) given on page 1

■ Scientific Objectives

1 Background

There is a nearly two orders of magnitude range in mass between the least massive star and our solar system's largest planet (Jupiter). For solar composition, the hydrogen-burning mass limit is believed to be about 0.075 to $0.08M_{\odot}$. Jupiter's mass is very nearly $0.001M_{\odot}$. Until quite recently, no celestial objects were known within this substellar / super-giant planet regime. The term "brown dwarf" was coined to refer to substellar objects at least in the top part (0.01 – $0.075M_{\odot}$) of the range.

The first brown dwarfs and extrasolar planets were found in 1995, ironically from three separate techniques yielding success at the same time. These are (1) radial velocity measurements of nearby stars, (2) imaging of young clusters and star formation regions, and (3) direct imaging searches for substellar companions to nearby stars, with or without special (ie. coronagraphic, interferometric) techniques. These resulted in initial discoveries, from the above techniques respectively, of 51 Peg B (Mayor and Quilloz 1995), Teide 1 and PPL 15 in the Pleiades (Rebolo et al. 1995; Basri, Marcy and Graham 1996) and Gliese 229B (Nakajima et al. 1995). The "floodgates" have opened for methods 1 and 2 (above), as literally dozens of close planetary companions have now been reported by several groups worldwide, while likely sequences of substellar objects have been found in several young clusters and star-forming regions. On the other hand, brown dwarf companions to nearby stars may turn out to be rare. Yet a fourth technique – infrared and deep optical surveys of the field – is now finding numerous likely brown dwarfs as individual objects in the solar neighborhood, objects not detected at the optical wavelengths of prior photographic sky surveys.

2 Field Sky Surveys and the L Dwarfs

Two surveys of the sky at infrared wavelengths are being undertaken. These are the Deep Near Infrared Survey (DENIS) by a European consortium, and the Two Micron All Sky Survey (2MASS), a consortium led by the University of Massachusetts and NASA's IPAC facility. The former is surveying the southern half of the sky, operating a telescope at the European Southern Observatory; 2MASS has telescopes in Arizona and Chile surveying the entire sky. The success of these projects in finding substellar field objects is due to the fact that, while very faint at optical wavelengths, some emit significant radiation at the JHK bands measured by the 2MASS telescopes (DENIS uses I band near 0.8μ in place of H band). That is, the brown dwarfs are characteristically cooler than the coolest M dwarf stars, and a new L spectral class has been defined for these objects (Delfosse et al. 1997, Kirkpatrick et al. 1999, hereafter K99).

The paper K99 defines the spectral properties of the various subtypes of L dwarfs (L0 to L8). They are believed to have effective temperatures between 2000 K or a bit higher and 1500-1600 K. At the higher T_{eff} , the molecules of TiO and VO which are the biggest absorbers at optical and red wavelengths (0.5 – 1μ) are predicted to form dust and perhaps

drop below the atmospheric layers. This causes the red spectra to change character from M to L type, as the red spectral region becomes more transparent. At near-infrared (JHK) wavelengths, CO and H₂O remain the dominant absorbers for both M and L types. Below about 1500 K, the prediction is that the dominant carbon molecule may switch from CO to CH₄, leading to dramatically different infrared spectra and colors. This is observed in the ~1,000 K brown dwarf GL 229B, which is classified a methane or T dwarf. Since methane is not observed in even the latest L type objects, 1,500 K is believed to approximate or bound the coolest of these objects.

At the time of this writing (May 1999), the 2MASS project alone has discovered nearly 100 L dwarfs. Extrapolation of the fields already observed to the full sky suggests that about 1500 L dwarfs might be detected in the survey. In 1999 the Sloan Digital Sky Survey (SDSS), which is very sensitive in the Z band (0.9 μ) to 20th magnitude, found the first two isolated methane dwarfs, objects like GL 229B (Strauss et al. 1999). Shortly thereafter, 2MASS reported the discovery of three more of these objects (Burgasser et al. 1999). As we shall see, these objects are predicted to be much more numerous than the L dwarfs per unit volume.

Using the spectroscopic information and the predictions of models, we have estimated a “temperature scale,” the relation between T_{eff} and the L spectral type. The luminosities of five objects have been measured via trigonometric parallaxes. However, the problem is that the masses and ages of the field L dwarfs are not known. Still, the detection of undepleted lithium in the atmospheres of about 1/3 of the sample indicates that at least this fraction are substellar. This conclusion relies on the predictions of interiors models that the configurations should be convective throughout. If there is lithium at the surface, lithium should not be depleted in the central regions because the temperatures are too low for fusion of either lithium or hydrogen. This “lithium test” appears validated by observation of a lithium luminosity boundary in both the Pleiades and Alpha Persei clusters – below which objects show the lithium feature, above which they do not. In both cases the boundary occurs at the luminosity predicted for depletion to terminate at the cluster’s age.

Now we show how the existence of a lithium depletion boundary as a function of mass and age helps us model the mass and age distributions of the L dwarfs discovered in a complete sample by 2MASS. In Fig. 1 the T_{eff} of evolutionary models of Burrows et al. (1997) are plotted vs age (in Gyr) for a sequence of stellar and substellar masses. The dark diagonal band indicate the locations where Li depletion occurs as a function of mass and age. Objects lying to the left of the band are predicted to show Li, those to the right will not. It can be noted that, for objects that have evolved to 1500-2000 K surface temperatures characteristic of the L dwarfs, Li is predicted to have been depleted if the mass is above 0.06-0.065 M_{\odot} . Detection of Li in the red spectrum of such an object is evidence that the object’s mass is below the above values, well into the substellar regime, and also that the lithium L dwarfs are young (0.1-1 Gyr) compared to the age of the Galactic disk. On the other hand, the absence of a Li feature does not prove that an object is above the stellar mass limit, as it could also have 0.06-0.075 M_{\odot} .

Reid et al. (1999, hereafter R99) have modelled the 2MASS sample to estimate the

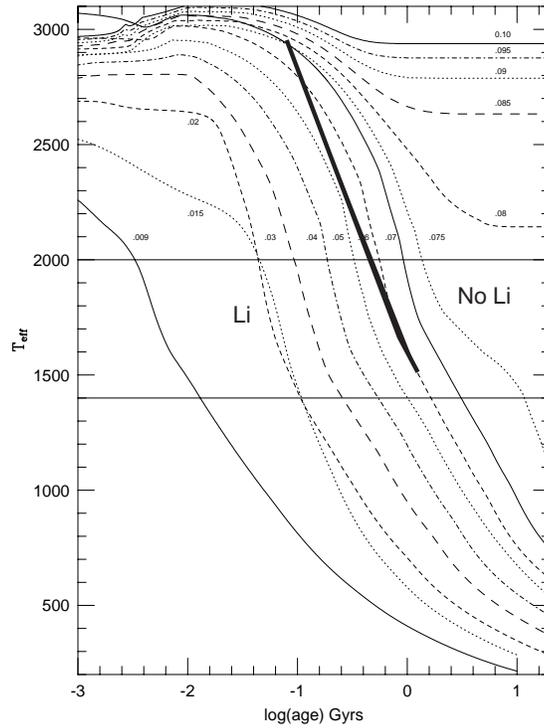


Figure 1: The effective temperature/age relation defined by the Burrows et al. (1993, 1997) models. The evolutionary tracks are plotted for masses between 0.009 and $0.10M_{\odot}$, individually identified on the diagram. The horizontal lines outline the T_{eff} range which correspond to the L dwarf spectral type. (Fig. 6 from R99)

implied number of brown dwarfs and their likely mass function. Looking again at Fig. 1, it may be noted that all objects showing lithium with T_{eff} between 1500-2000 K must have ages of less than 10^9 years – depending on how low is the mass, the age could even be one to two orders of magnitude less. However, the near-infrared surveys should therefore find preferentially *the youngest and most massive* of the population of field brown dwarfs.

If it can be assumed that the Galactic disk star formation rate has been occurring significantly for many Gyr – and the mass function (MF) is also significant well into the substellar mass range – then it is obvious from the figure that many more objects are predicted to be found in the lower right portion of the diagram. R99 assume a constant star formation rate for 0.10^{10} years, with an MF characterized by a Salpeter-like power law of index α into the substellar mass range, and that there is a (arbitrary) cutoff of this MF (at $0.01M_{\odot}$). The evolutionary models whose tracks are plotted in Fig. 1 are used to predict the luminosities and temperatures as a function of mass and age, to reproduce the 2MASS sample of low temperature objects, and the fraction of L dwarfs where the Li resonance doublet is detected. Since an object near $0.01M_{\odot}$ spends so little time at L dwarf temperatures, there is also a natural cutoff in the ability of the near-infrared surveys to detect the low end of the possible range, and hence there is little sensitivity to the assumed cutoff mass, provided it is well below the stellar mass limit.

The simulations indicate that, in a fixed volume surrounding the Sun, there should be of the order 10 times as many objects cooler than 1500 K, than those found near and above this temperature. The space density actually calculated for substellar objects is of the order $0.1pc^{-3}$. This would imply that of the order 50 substellar objects lie within 5pc of the Sun! However, most of these are predicted to be so cool they would be fainter than the magnitude limits of the 2MASS and DENIS surveys.

The distributions of these predicted celestial bodies vs. absolute M_K , M_{bol} and T_{eff} are shown as Fig. 2, taken from R99. The numbers are normalized to the sphere with radius 8 pc around the sun. Distributions are shown for assumed power law slopes α of (-)1 and 2 (that is, increasing numbers per interval of decreasing mass. The R99 paper finds a precarious best fit to $\alpha = -1.3$. In all three plots it is seen again that an order of magnitude more objects remain to be found that are cooler than the 2MASS L dwarf sample. These so-called T dwarfs like GL 229B are just now being found by SDSS and the infrared surveys. Indeed, these discoveries are consistent with the assumption that field brown dwarfs spanning a range of temperature inhabit the solar neighborhood. If the substellar sequence found in the Pleiades is typical of the field (Rebolo et al. 1999), brown dwarfs exist down to at least $35M_J$, perhaps with a mass function slope rising modestly at decreasing masses. A much-younger candidate in Orion has an estimated mass near $15M_J$.

In fact, there is no reason to dismiss entirely the possibility that extrasolar planets below $10M_J$ may also exist in the field. Even if fragmentation models suggest that single objects may not become self-gravitating cores below a particular mass limit, the existence of massive extrasolar planets in close, eccentric orbits underscores the possibility that such planets may be ejected from circumstellar disks by three body interactions. Of course any isolated, low mass neighbors may be extremely faint unless they are young. A $1M_J$ planet is predicted by

ASWG DRM Proposal
A Spectroscopic Study of Cool, Field Brown Dwarf Neighbors

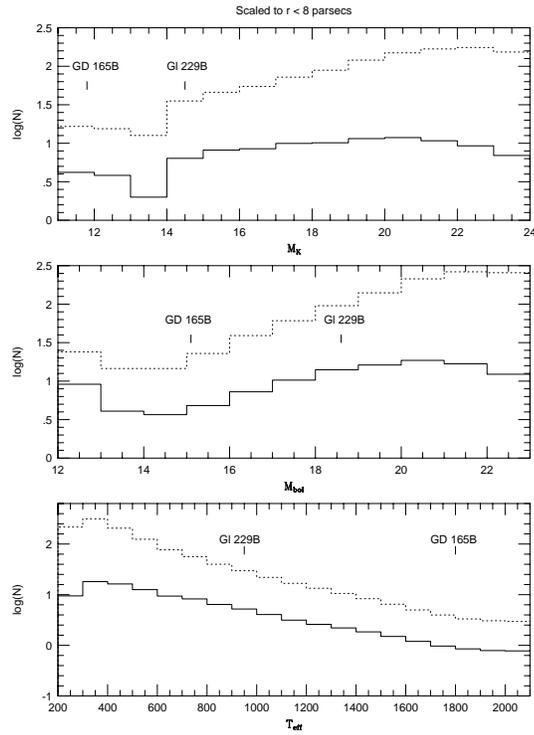


Figure 2: The $2.2\mu\text{m}$ and bolometric luminosity functions and the effective temperature distribution predicted by the models of R99 for a constant formation rate, IMF slopes α of -1 (solid line) and -2 (dashed), extending to a mass cutoff of $0.01M_{\odot}$. (Fig. 9 from R99)

Burrows et al. (1997) to cool below 200 K in $< 1\text{Gyr}$, and a $5M_J$ object will reach 300 K.

3 Detection and Spectroscopic Followup of the Sun’s Coolest Neighbors

Burrows et al. (1997) have done an initial modelling for cool giant planets at temperatures between the L dwarfs and Jupiter. Some synthetic spectra are shown in Fig. 3. The top plot of the sequence is for a T_{eff} near 1,000 K, the bottom 130 K. Below 1,000 K the bulk of the energy is radiated in the thermal infrared, with a peak near 4.5μ and a flat energy distribution (except for molecular bands) out to 10μ . Collision-induced absorption of H_2 suppresses emissions longward of this wavelength. Note that none of the hypothetical objects placed at 10 pc in this figure would be detectable with 2MASS, but significant numbers are predicted by R99 at much closer distances. Even at the lower temperatures, the J, H and Z bands remain relatively transparent windows for radiation to escape, the Sloan and infrared surveys can be expected to find some of these solar neighbors over the next several years (1999-2002). Indeed, at the time of this writing, about a half-dozen cooler T-dwarfs have been found with 2MASS and SDSS. Moreover, SIRTf, SOFIA, and large ground-based telescopes have greater reach via mid-infrared wavelengths. The 4.5μ region is actually the prime wavelength for detection. If the Next Generation Sky Survey (NGSS) explorer mission is flown, it may be the most efficient means of identifying an ideal target list for spectroscopic study by NGST at the thermal infrared wavelengths at which they may be optimally studied.

Our assumption for this proposal is that the above facilities (or others) will find a suitable target list for followup spectroscopic observation with the NGST. The goal would primarily be the detailed studies of the chemical composition and physical parameters for this new class of astrophysical object between giant planets and low mass stars. This goal is properly part of the NASA Origins mission, because these objects link star and planet formation, either directly in the field or possibly ejected from planetary system.

There is reason to anticipate that the atmospheric properties may be quite interesting. At T_{eff} below 1,300 K the neutral alkali elements (K, Na, Li, Cs, Rb), so prominent in the red spectra of L dwarfs, are predicted to precipitate out mainly into their salts.

Followup studies of GL 229B (~ 950 K) indicate an atmosphere that is more complex than that of a low mass star, with evidence of mixing processes. In particular, Cs I and CO are both detected in the spectra, although they shouldn’t be present in that form according to equilibrium models (cf. Burrows & Sharp 1999). These species are apparently mixed upwards from warmer layers below the photosphere. Such cool brown dwarfs may also exhibit spatial and time dependences, as does Jupiter. Brown dwarf “weather” processes could become more important at lower temperatures. Below about 600 K the dominant nitrogen molecule is NH_3 , not N_2 . Below ~ 400 K, water clouds form at or above the photosphere. Below 200 K, ammonia clouds form, as observed in Jupiter.

It is also possible – as with Jupiter – that magnetic dynamos may operate in objects between the masses of Jupiter and low mass stars. Jupiter possesses most of the angular momentum of the solar system, and a strong magnetic field. There is some evidence that even

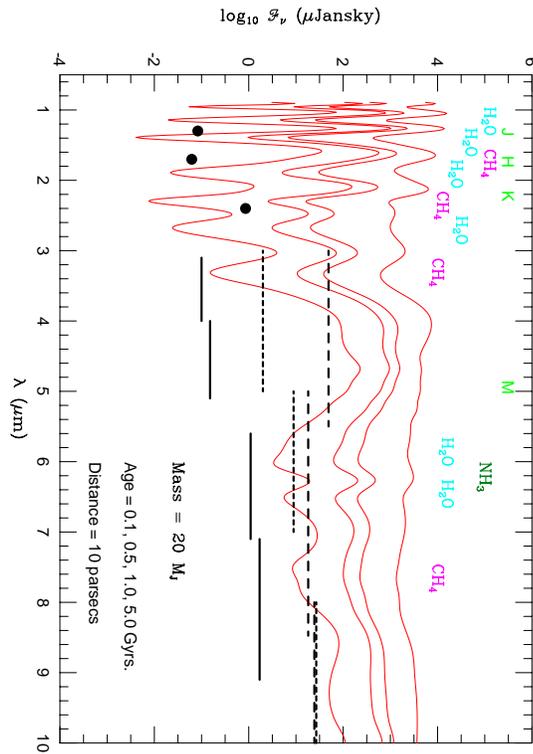


Figure 3: Flux in mJy for an assumed distance of 10 pc vs. wavelength in μm for a $20M_J$ object at ages 0.1, 0.5, 1.0 and 5.0 Gyr (descending order). Superposed are the positions of the J, H, K, and M bands, the estimated sensitivities of the three NICMOS cameras (filled circles), ISO (long dashed lines), Gemini/SOFIA (short dashed line) and SIRTTF (filled lines). Strong absorption bands of some important molecules are marked. (Fig. 19 from Burrows et al. 1997)

very low mass stars spin down much more slowly than solar-type stars, retaining dynamo activity for more than a Gyr. A powerful chromospheric “flare” event has already been detected in one 2MASS counterpart, a borderline L dwarf (Liebert et al. 1999). In Jupiter’s case, the interaction with the inner, tidally-distorted, Galilean satellites produces among other things an emission reversal of the 7.8μ methane absorption feature. Certainly the cool brown dwarf neighbors of the Sun might also harbor circumplanetary disks in their youth, from which satellite (or their own planetary) systems might form.

References:

- Basri, G., Marcy, G., & Graham, J.R. 1996 ApJ, 458, 600
- Burgasser, A.J., Kirkpatrick, J.D., Brown, M.E., Reid, I.N., Gizis, J.E., Dahn, C.C., Monet, D.G., Beichman, C.A., Liebert, J., Cutri, R.M., and Skrutskie, M.F. 1999, Ap.J. in press.
- Burrows, A., Hubbard, W.B., Saumon, D., & Lunine, J.I., 1993 ApJ, 406, 158
- Burrows, A., Marley, M., Hubbard, W.B., Lunine, J.I., Guillot, T., Saumon, D., Freedman, R., Sudarsky, D., & Sharp, C. 1997 ApJ, 491, 856
- Burrows, A. & Sharp, C.M. 1999 ApJ, 512, 843
- Delfosse, X., Tinney, C.G., Forveille, T., Epchtein, N., Bertin, E., Borsenberger, J., Copet, E., de Batz, B., Fouque, P., Kimeswenger, S., Le Bertre, T., Lacombe, F., Rouan, D. & Tiphene, D. 1997, Astr. Ap., 327, L25
- Kirkpatrick, J.D., Reid, I.N., Liebert, J., Cutri, R.M., Nelson, B., Beichman, C.A., Dahn, C.C., Monet, D.G., Skrutskie, M.F., and Gizis, J. 1999b, Ap.J. July 20 in press (K99)
- Liebert, J., Kirkpatrick, J.D., Reid, I.N., & Fisher, M.F. 1999 Ap.J. July 10, in press
- Mayor, M. & Queloz, D. 1995 Nature, 378, 355
- Nakajima, T., Oppenheimer, B.R., Kulkarni, S.R., Golimowski, D.A., Matthews, K. & Durrance, S.T. 1995 Nature, 378, 463
- Oppenheimer, B., Kulkarni, S.R., Matthews, K., & van Kerkwijk, M.H., 1998 ApJ, 502, 932
- Rebolo, R., Zapatero Osorio, M.R., & Martin, E.L., 1995 Nature, 377, 129
- Rebolo, R., Zapatero Osorio, M.R., & Martin, E.L., 1999, preprint
- Reid, I.N., Kirkpatrick, J.D., Liebert, J., Burrows, A. Gizis, J., Burgasser, A., Dahn, C.C., Monet, D.G., Cutri, R.M., Beichman, C.A., & Skrutskie, M.F., ApJ, in press (R99)
- Strauss, M.A. et al. 1999, ApJ in press.

■ NGST Uniqueness/Relationship to Other Facilities

The majority of our target list is anticipated to be brown dwarfs cooler than GL 229B (~ 950 K) and close to the Sun. Only a half dozen such objects may be listed in the target list today. It is assumed that it will be possible several years from now to choose the best discoveries from the ground-based sky surveys SDSS, 2MASS, DENIS, SIRTF and possibly NGSS as outlined earlier. A SIRTF Legacy project using the IRAC bands beginning at 4.5μ in a $\sim 1,000$ square degree field survey may be proposed to find extremely cool neighbors emitting too little at $1-2\mu$; 4.5μ is generally where the maximum flux escapes at all T_{eff}

below 1,000 K.

These photospheres emit most radiation between 4μ and 10μ , at pretty much all temperatures below 1,000 K. The ground-based photometry and spectroscopy of GL 229B (Oppenheimer et al. 1998) shows how limited the analysis of these atmospheres can be, when so restricted in bandpass and sensitivity, even when a ground-based telescope as large as 10-meters in aperture is used. A comprehensive, medium resolution spectrum from J-H to longward of 10μ addresses the several questions concerning the nature of this new class of atmospheres discussed in the text. Spectroscopy with NGST is unique longward of 2.5μ and would be extraordinarily sensitive at shorter wavelengths with no gaps due to atmospheric absorption.

■ Observing Strategy

Our target list consists of GL 229B, two DENIS and 2MASS field brown dwarfs (confirmed by the detection of Li I), five very recently confirmed T-dwarfs (confirmed by the detection of methane) plus three hypothetical targets cooler but closer to the Sun which our modelling (Fig. 2) indicates that existing and planned surveys should find over the next decade.

■ Special Requirements

It would be rewarding to study the possible time (and spatial) dependent “weather” phenomena for a selection of these objects too cool or faint for effective ground-based study. This would help in comparing properties between Jovian planets and low mass stars. It is possible that rotation periods might even be determined if there are substantial spatial variations; it is possible that $v \sin I$ will be too small for a spectroscopic determination (at R of 10000) of most objects. Our observing plan includes many visits to GL 229B and typically five visits to the remaining sources which are spread over the predicted luminosity function of R99 (Fig. 3).

Minimum Spectral Resolution: 5000 at $7\mu\text{m}$

■ Precursor/Supporting Observations