Brown Dwarf Companions to Young Solar Analogs: An Adaptive Optics Survey Using Palomar and Keck

by

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Thesis by
Stanimir A. Metchev

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Acknowledgements

Stan, congratulations. I just can't believe you made it.
Cheers, Jeff Hickey

Having left this for last, I now finally have the peace of mind and hindsight to recollect and thank all the people that supported me, guided me, and kept me sane throughout my graduate work.

First and foremost are my parents, Anguel and Kalitchka, whom I have rarely seen for more than 2 weeks a year over the past 10 years, but whose faith in me has always pushed me forward, even from the distance of my home country, Bulgaria. I thank my father for showing me the stars and making me aware of a Universe open to endless exploration. I thank my mother for her unconditional support, even when she thought that I should have taken up Economics, rather than Astronomy. My parents and my brother, Anton, are the three people in this world that have defined how I think, feel, and love.

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With this I come to my close friends. I thank all of you who kept me sane over the years and months before my defense, who came to support me during the defense itself, and who celebrated with me afterwards. In particular, I need to acknowledge my office mates Dave Sand, Kevin Bundy, and Josh Eisner. Between them and Russel White, there would always be a good occasion for mid-week drinks at Amigos or at Burger Continental. Also, having gone through the job-hunting and thesis ordeals at the same time as Josh and Dave has certainly helped me maintain focus and keep the pace.

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Abstract

We present results from an adaptive optics survey conducted with the Palomar and Keck telescopes over 3 years, which measured the frequency of stellar and sub-stellar companions to Sun-like stars. The survey sample contains 266 stars in the 3–10000 million year age range at heliocentric distances between 8 and 200 parsecs and with spectral types between F5–K5. A sub-sample of 101 stars, between 3–500 million years old, were observed in deep exposures with a coronagraph to search for faint sub-stellar companions. A total of 288 candidate companions were discovered around the sample stars, which were re-imaged at subsequent epochs to determine physical association with the candidate host stars by checking for common proper motion. Benefiting from a highly accurate astrometric calibration of the observations, we were able to successfully apply the common proper motion test in the majority of the cases, including stars with proper motions as small as 20 milli-arcseconds year^{-1}.

The results from the survey include the discovery of three new brown dwarf companions (HD 49197B, HD 203030B, and ScoPMS 214B), 43 new stellar binaries, and a triple system. The physical association of an additional, a priori-suspected, candidate sub-stellar companion to the star HII 1348 is astrometrically confirmed. The newly-discovered and confirmed young brown dwarf companions span a range of spectral types between M5 and T0, and will be of prime significance for constraining evolutionary models of young brown dwarfs and extra-solar planets.

Based on the 3 new detections of sub-stellar companions in the 101 star sub-sample and following a careful estimate of the survey incompleteness, a Bayesian statistical analysis shows that the frequency of 0.012–0.072 solar-mass brown dwarfs in 30–1600 AU orbits around young solar analogs is $6.8^{+8.3}_{-4.9}\%$ (2σ limits). While this is a factor of 3 lower than the frequency of stellar companions to G-dwarfs in the same orbital range, it is significantly higher than the frequency of brown dwarfs in 0–3 AU orbits discovered through precision radial velocity surveys. It is also fully consistent with the observed frequency of 0–3 AU extra-solar planets. Thus, the result demonstrates that the radial-velocity “brown dwarf desert” does not extend to wide separations, contrary to previous belief.

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Chapter 1

Introduction

Brown dwarfs make rare companions to stars. This is the current belief in the field of sub-stellar astronomy, based both on precision radial velocity (RV) surveys, probing orbital separations of <5 astronomical units (AU; Marcy & Butler, 2000), and on direct imaging efforts, probing orbital separations >100 AU (Oppenheimer et al., 2001; McCarthy & Zuckerman, 2004). However, while the radial velocity "brown-dwarf desert" remains nearly void, even after the discovery of numerous extra-solar planets over the last decade, the direct imaging brown-dwarf desert appears to be, slowly but surely, becoming populated. How confident are we of the lack of brown dwarfs in wide orbits around stars? Does the direct imaging brown-dwarf desert indeed exist? The few wide brown-dwarf companions that *have* been imaged around main sequence stars have provided a disproportionately large wealth of information on the physics of sub-stellar objects, in comparison to their isolated counterparts. A prime example for this is Gl 229B–the first decidedly sub-stellar object to be discovered through imaging (Nakajima et al., 1995) and still the prototype for the coolest objects at the bottom of the main sequence. The reason for this success is the scientifically optimal environment inhabited by brown-dwarf secondaries in wide orbits. Unlike close-in sub-stellar companions found from RV surveys, wide ($> 10 - 100$ AU) brown-dwarf companions are directly accessible for imaging and spectroscopy, thus allowing a characterization of their photospheric and thermodynamic properties. Unlike isolated free-floating brown dwarfs, brown dwarfs in multiple systems have well-constrained ages (when physically associated with a star) and may allow dynamical determinations of their mass (when in close binaries). That is, wide brown-dwarf companions to stars offer the best opportunity to fully determine the properties and trace the evolution of sub-stellar objects. From a scientific point of view, it would be rather unfortunate, if wide brown-dwarf companions to stars did indeed turn out to be rare.

With the present work, we aim to obtain a decisive determination of the frequency of wide brown-dwarf companions to stars. By targeting a large number of young Sun-like stars, we aim to establish a sample of young brown dwarfs with a well-determined age, whose physical properties can be used to improve our current knowledge of sub-stellar objects, and that can serve as reference in future studies.

The introductory chapter continues with a brief overview of definitions and brown-dwarf properties (§1.1). The main scientific goals of the thesis in their justification in the context of sub-stellar astronomy, are set forth in §1.2. Section §1.3 presents the observational challenges and constraints, and §1.4 summarizes the adopted observational approach for achieving the goals. Section §1.5 outlines the contents of the thesis by chapters.

1.1 Brown Dwarfs: A Brief Summary of Properties

We start with a brief overview of the physical and observable properties of brown dwarfs, and of their perceived place in between stars and extra-solar planets.

Brown dwarfs are the most recently discovered objects at the bottom of the main sequence. The new spectral types coined for these objects–L and T (Kirkpatrick et al., 1999)–represent the first major extension of the standard Morgan-Keenan OBAFGKM classification scheme (Cannon & Pickering, 1901; Morgan et al., 1943). Implied in this taxonomic expansion is the recognition of the discovery of a fundamentally new type of object. Their masses are too low, less than 0.07–0.08 of a solar mass ($M_\odot$; our Sun is $1M_\odot$), to ever raise their core temperatures to sufficiently high values ($\sim 3 \times 10^6$ K) to induce hydrogen fusion (Kumar, 1963; Hayashi & Nakano, 1963; Burrows & Liebert, 1993; Baraffe et al., 1995). Thus, brown dwarfs are "sub-stellar" objects, and, unlike stars, cool eternally. The distinction between stellar and sub-stellar objects is illustrated in Figures 1.1 and 1.2, which show theoretical luminosity evolution tracks for low-mass stars and brown dwarfs from Burrows et al. (1997, 2001). The bifurcation in the luminosity and effective temperature ($T_{\rm eff}$) evolution at an age of 0.5–1.0 giga-years (Gyr) straddles the hydrogen-burning mass limit. The exact value of this limit is known to be metallicity dependent, ranging from 0.083–0.085$M_\odot$ at zero metallicity, to 0.072–0.075$M_\odot$ at solar metallicity (Burrows & Liebert, 1993; Burrows et al., 1997; Chabrier & Baraffe, 1997; Chabrier et al., 2000). Figure 1.1 also demonstrates that, even though massive brown dwarfs may start out with star-like luminosity ($\gtrsim 10^{-3}$ solar luminosities [$L_\odot$]), they progressively dim with age to the point where, after 0.5 Gyr all sub-stellar objects are less luminous than the dimmest, lowest-mass, stars. In terms of effective temperature ($T_{\rm eff}$) and spectral type, brown dwarfs may start as star-like objects hotter than 2200 K, with spectral type M (Kirkpatrick et al., 1999). As they get older, brown dwarfs pass through the later L ($1400 \lesssim T_{\rm eff} \lesssim 2200$ K; Kirkpatrick et al., 1999; Leggett et al., 2001) and T ($T_{\rm eff} \lesssim 1300$ K; e.g., Burgasser et al., 2002) spectral types (Fig. 1.2).

In sub-stellar interiors luminosity and gas pressure are insufficient to counteract gravity in the equation of state. Brown dwarfs are thus compact objects, partially supported against gravitational collapse by electron degeneracy pressure (at early spectral types) and Coulomb pressure (at late spectral types; Stevenson, 1991; Burrows & Liebert, 1993). Hence, their radii R vary only slowly with mass M. The exact functional form of $R(M)$ is dependent on the relative partition of gas, electron degeneracy, and Coulomb pressure, though for most of the sub-stellar regime varies between $R \propto M^{-1/3}$ and $R \propto M^0$ (Burrows & Liebert, 1993), i.e., the radii of brown dwarfs are nearly mass-independent.

More detailed, in-depth reviews of the physics of sub-stellar objects can be found in Stevenson (1991); Burrows & Liebert (1993); Chabrier & Baraffe (2000), and Burrows et al. (2001).

1.1.1 Similarities to Stars

Despite their fundamentally different nuclear physics from that of main sequence (MS) stars, brown dwarfs are expected to follow the same mode of formation as (at least low-mass) stars (Bate et al., 2003; Padoan & Nordlund, 2004). That is, there does not exist an a priori set switch in nature that would distinguish between stellar and sub-stellar objects at the epoch of formation, other than the availability of sufficient accretable mass in the parent environment of the objects. Indeed, spectroscopic studies of the initial mass function in 1–5 million-year (Myr)

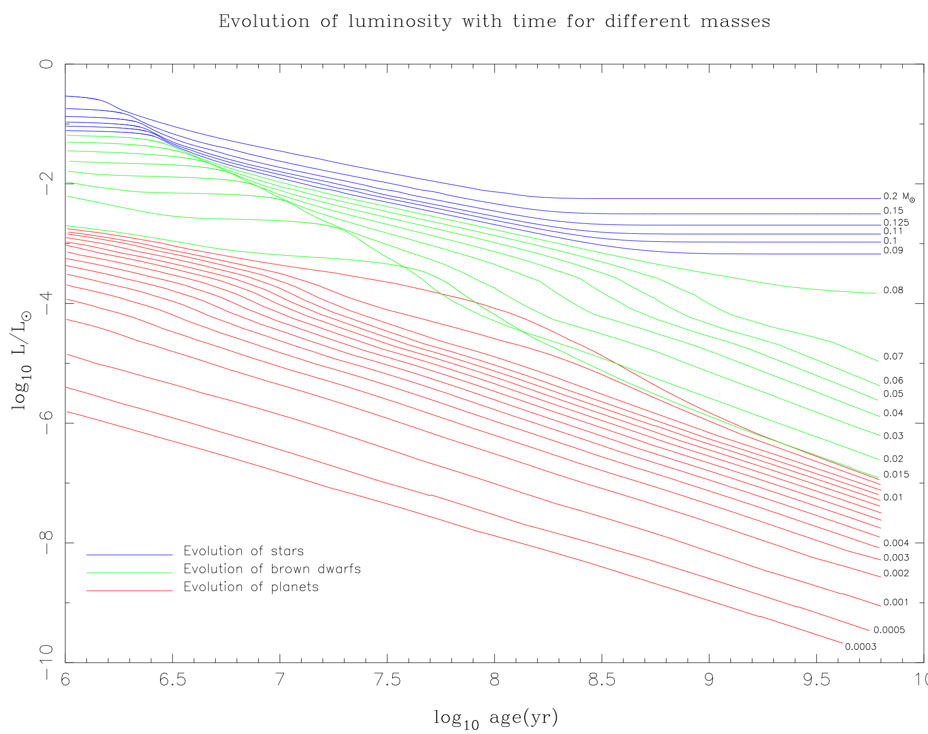

Figure 1.1: Sub-stellar and low mass stellar luminosity evolution tracks from Burrows et al. (1997). Object masses (in $M_\odot$) are marked to the right-hand side of the corresponding luminosity tracks. The top set of lines (0.08–0.2$M_\odot$) shows stellar evolutionary tracks, the middle set (0.015–0.08$M_\odot$) traces brown-dwarf tracks, and the lowest set (0.0003–0.015$M_\odot$) traces "planet" tracks. (Courtesy of A. Burrows)

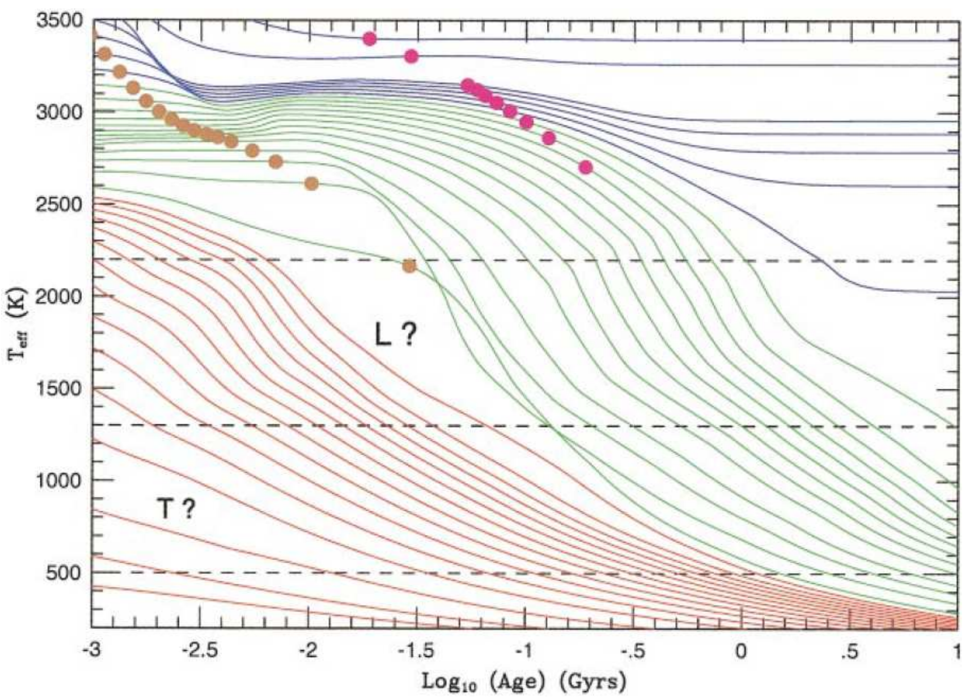

Figure 1.2: Evolution of the effective temperature of low-mass stars and brown dwarfs, as predicted by Burrows et al. (2001). The sets of continuous lines are the same as in Figure 1.1. Horizontal dashed lines mark the approximate effective temperature limits of the M, L, and T spectral types. Note that the lowest-mass ($\approx 0.08 M_{\odot}$) hydrogen-burning stars at >3 Gyr ages are L dwarfs, while all $>0.010 M_{\odot}$ brown dwarfs start as M dwarfs. The two sets of filled circles (not discussed in the present text) mark the 50% depletion loci for deuterium (left) and lithium (right). (Burrows et al., 2001)

old star-forming regions (Briceño et al., 2002; Luhman et al., 2003b; Slesnick et al., 2004) show no abrupt change in the abundance and spectroscopic signatures between objects above and below the hydrogen-burning mass limit. This smooth transition confirms that brown dwarfs are created as a result of a low-mass extension of the star-formation process. Discoveries of brown dwarfs have thus shed new light on the range of possible outcomes in environments of star formation.

1.1.2 Similarities to Planets

Given the similarity between brown dwarfs and main sequence stars, it may come as a surprise that brown dwarfs also share common features with planets. Nevertheless, starting with spectral type T0 and progressing toward later spectral types, the near-IR spectra of brown dwarfs exhibit increasingly stronger molecular absorption by CH_4 and H_2 (Burgasser et al., 2002), in addition to the H_2O absorption already present in L dwarfs (Kirkpatrick et al., 1999). Conversely, absorption by refractory elements (VO, TiO, and FeH), as characteristic of low-mass M stars in the optical and near-IR (e.g., Leggett et al., 2001), decreases in strength in the L dwarfs, and disappears in the Ts. Thus, at a spectral type of T6.5 ($T_{\rm eff} \sim 900$ K; Burgasser et al., 2002), the methane- and water-absorption dominated spectrum of the first discovered brown dwarf, Gl 229B (Nakajima et al., 1995; Oppenheimer et al., 1995), resembles the spectra of solar-system objects, Jupiter and Titan, more than those of stars. This follows the theoretical expectation, that the ultimate state of a cooling brown dwarf, beyond the end of even the expanded spectral sequence, is a cold, fully degenerate object: much like a planet. Equations of state for degenerate interiors also dictate that the radii of L and T dwarfs are similar to those of giant gaseous planets, such as Jupiter.

1.1.3 A Matter of Terminology: Low-mass Brown Dwarfs vs. Planets

It is evident from the preceding description (§1.1.1 and §1.1.2) that brown dwarfs occupy an intermediate regime between those of stars and giant planets. High-mass brown dwarfs are likely to be as indistinguishable from stars at young ages, as low-mass and/or old brown dwarfs are from giant planets. Nevertheless, because of the existence of a minimum hydrogen-burning mass, there is a clear separation between brown dwarfs and stars in evolutionary context. Hence, the hydrogen-burning mass limit, albeit not emphasized by an observable transition between the photospheric properties of stars and brown dwarfs at young ages, is defined as the boundary separating the stellar from the sub-stellar regime.

At the low-mass end, the distinction between brown dwarfs and planets is less well-defined. Besides the similarities between their interiors and sizes, the mass regimes of known radial-velocity (RV) extra-solar planets and directly imaged brown dwarfs seem to overlap, in the range between 5 and 15 times the mass of Jupiter ($M_{\rm Jup}$[1]). This comes in contrast to the fact that the physical processes traditionally perceived as leading to the formation of planets—accretion of planetesimals and gas in a circum-stellar disk (e.g., Lissauer, 1993)—and of more massive, isolated objects (stars and brown dwarfs)—gravo-turbulent fragmentation of a molecular cloud (Bodenheimer et al., 1980; Padoan & Nordlund, 2004)—are very distinct. Recent theories have

[1] $1 M_{\rm Jup} = 0.954 \times 10^{-3} M_\odot \approx 0.001 M_\odot$

also proposed a hybrid process—gravitational instability in a massive circum-stellar disk—for the creation of both giant planets (Boss, 2002) and brown dwarfs and low-mass stars (Bate et al., 2002). Regardless of the outcome of the theoretical effort to model planet and brown-dwarf formation, the evidence for overlap between the two mass regimes is probably real.

The lack of distinction at the planet/brown-dwarf boundary has spurred some scientific debate as to what exactly should be considered a planet and what a brown dwarf. Oppenheimer et al. (2000b) have proposed a distinction analogous to the one established at the stellar/sub-stellar boundary: deciding the classification of an object based on its thermonuclear fusion capability. Although brown dwarfs do not possess sufficient mass to maintain hydrogen fusion, objects more massive than 0.013–0.015$M_\odot$ (depending on metallicity) are expected to undergo a brief deuterium-burning phase (Burrows et al., 1997). The deuterium-burning phase is seen as a region of slower luminosity and effective temperature decline in $> 0.013\ M_\odot$ objects at 3–30 Myr ages in Figures 1.1 and 1.2. Oppenheimer et al. (2000b) choose to define such deuterium-burning objects as "brown dwarfs" and reason that lower-mass objects, which never fuse deuterium, should be referred to as "planets." Alternative to this is the traditional view of a planet, upheld by McCaughrean et al. (2001), as an object forming in a circum-stellar disk. The latter definition reserves the term "brown dwarf" for sub-stellar objects formed through a star-like process.

We will generally adhere to the latter terminology, recognizing the fundamental difference between the likely modes of formation of planets in our solar system and of brown dwarfs found in isolation. However, also recognizing the overlap in mass between the latter and known extra-solar planets, we will occasionally refer to $<13M_{\rm Jup}$brown dwarfs as "planetary-mass objects" in the context of their gravitational association with main sequence stars.

1.1.4 Theoretical Models of Sub-stellar Evolution

Because sub-stellar objects never go through a star-like main-sequence phase, their luminosities and effective temperatures are functions of both mass and age. Observational brown-dwarf science is thus heavily reliant on theoretical models to accurately predict masses and/or ages for sub-stellar objects. The present study will not be an exception, though model predictions will be tested against the limited existing body of empirical data, whenever possible and needed.

Two suites of sub-stellar evolutionary models are used predominantly in the brown-dwarf community, originally due to theoretical teams at the University of Arizona (Burrows et al., 1997)[2] and at École Normale Supérieure de Lyon (Chabrier et al., 2000; Baraffe et al., 2003).[3] The predictions from the two groups are consistent to within 20% in mass at <1 Gyr ages. The present investigation will draw on comparisons to both sets of models whenever mass estimates of specific sub-stellar objects are required. Whenever calculations of solely upper limits are needed, the Lyon group models will be adopted. These offer predicted photometry for sub-stellar objects and low-mass stars over a vast range of masses (0.0005-0.1 $M_\odot$) and ages (1 Myr–10 Gyr) in a convenient tabular format.

The Lyon models come in two flavors: DUSTY (Chabrier et al., 2000) and COND (Baraffe et al., 2003), depending on the treatment of dust opacity in the brown-dwarf photosphere. The DUSTY models take into account the formation of dust in the equation of state, and its scattering and absorption in the radiative transfer equation. In this set of models, it is assumed

[2]Publicly available at http://jupiter.as.arizona.edu/~burrows/
[3]Publicly available at http://perso.ens–lyon.fr/isabelle.baraffe/

that dust species remain where they form, according to chemical equilibrium conditions. These models are most appropriate for $T_{\rm eff} \gtrsim 1500$ K objects (L dwarfs). For cooler, $T_{\rm eff} \lesssim 1300$ K, objects (T dwarfs), the COND evolutionary tracks model the spectroscopic and photometric properties better (Baraffe et al., 2003). The COND models are based on the coupling between interior and non-grey atmosphere structures. The models neglect dust opacity in the radiative transfer equation, and are applicable when all grains have gravitationally settled below the photosphere.

Neither of the two sets of models from the Lyon group account well for the photometric properties of L/T transition objects with effective temperatures in the 1300–1500 K range. The proper discussion of this issue requires cloud condensate models (e.g., Ackerman & Marley, 2001; Tsuji, 2002; Cooper et al., 2003), none of which however have been tested in evolutionary context. For this temperature range, we will adopt the COND models, which predict absolute near-IR magnitudes that are more consistent with those of late L and early T dwarfs with known trigonometric parallaxes (Fig. 1.3).

1.2 How Frequent are Brown Dwarf Companions and Why Study Them?

Returning to the principle motivation for this work, we re-iterate the presently established view on the frequency of brown dwarfs around stars. Brown dwarfs make rare companions to stars. The result has been borne out of the prolonged radial velocity (RV) effort to detect sub-stellar (i.e., brown dwarfs and planets) companions to stars, even before RV precision was sufficiently high to allow the detection of extra-solar planets. With more than 150 RV extra-solar planets now discovered and less than 10 possible brown dwarfs among them, the dearth of brown-dwarf secondaries in precision RV surveys remains so dramatic, compared to the relative abundance of planetary and stellar companions, that the phrase "brown-dwarf desert" is still as pertinent nowadays as when it was originally introduced (Marcy & Butler, 2000). The term provides a vivid representation not only of the lack of sub-stellar companions of intermediate mass between those of stars and planets, but presumably also of the tremendous scientific and psychological toil of the pioneering RV teams, before perseverance and technological progress laureated their efforts with success.

However, precision RV surveys paint only a partial picture of other stellar systems. They are sensitive only to objects with orbital periods of duration comparable to the survey time-span: presently $\leq$17 years for the longest-running precision RV surveys, corresponding to orbital semi-major axes of $\leq$5–7 AU from solar-mass stars. At wider orbital separations, corresponding to the gas and ice giant planet zones (5–40 AU) in the solar system, and beyond, little is known. Sub-stellar objects orbiting at >10 AU take too long to complete their orbits to incur a conclusive velocity trend in present RV surveys.

Our knowledge of sub-stellar multiplicity at such wide separations derives exclusively from imaging efforts. At small heliocentric distances, wide orbital companions may be sufficiently well-separated from their host stars to be resolved in direct images of the pair. Contrarily to RV surveys, the greater the orbital separation between the primary star and the secondary companion, the easier it is to detect the companion (at a fixed heliocentric distance). For example, given ability to obtain sufficiently sensitive high-contrast imaging data at $\geq 0.5''$, the entire giant planet region outwards of 5 AU can be imaged around a nearby star at 10 pc. In this

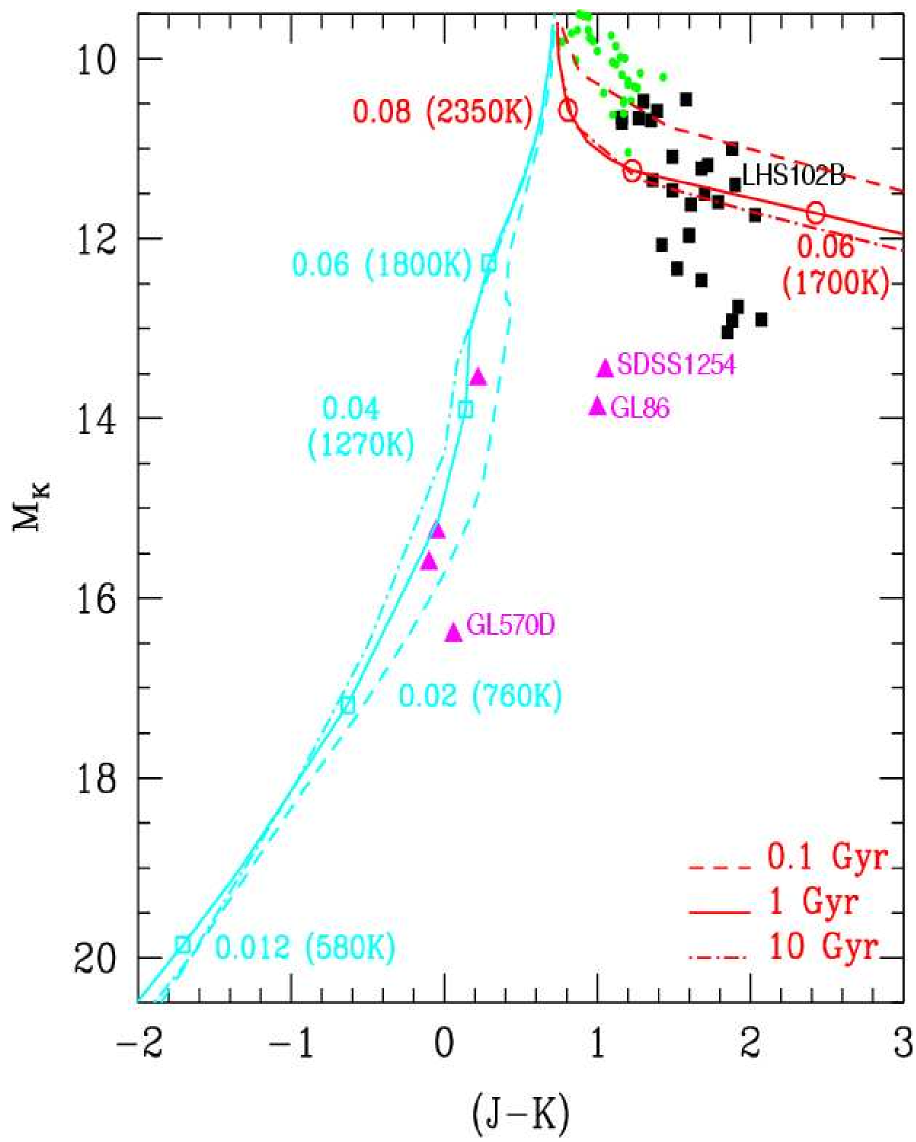

Figure 1.3: Color-magnitude diagram $(J-K)-M_{\mathrm{K}}$. Observations are taken from Leggett (1992) (mostly for M-dwarfs) and Dahn et al. (2002). Also shown: LHS 102B (EROS Collaboration et al., 1999), GL 86B[5] (Els et al., 2001). M dwarfs are shown by dots, L dwarfs by filled squares, and T dwarfs by triangles. DUSTY isochrones (Chabrier et al., 2000) are displayed in the upper right part of the figure, for different ages, as indicated. The COND isochrones (Baraffe et al., 2003) are displayed in the left part of the figure. Some masses (in $M_{\odot}$) and their corresponding T_{eff} are indicated on the 1 Gyr isochrones by open squares (COND) and open circles (DUSTY). The names of two L/T transition objects and of the faintest T-dwarf known with parallax are indicated. (Baraffe et al., 2003)

manner, precision RV and direct imaging surveys explore two complementary orbital realms for sub-stellar companions to nearby stars. However, unlike RV monitoring, which can reveal sub-stellar companions a fraction of a Jupiter in mass, direct imaging searches for sub-stellar secondaries to stars are still constrained to companions of multiple Jupiter masses or larger: mainly brown dwarfs. Any sub-stellar companions imaged around other stars will therefore be more massive than most of the known solar system planets. [6]

While the pace of RV discoveries has increased steadily since the detection of the first extra-solar planet (Mayor & Queloz, 1995), despite concentrated efforts from a number of teams, the rate of brown-dwarf companions discovered via direct imaging has been steadily slow for most of the same period, despite concentrated efforts from several groups. Two large direct imaging surveys for sub-stellar companions (Oppenheimer et al., 2001; McCarthy, 2001) have produced only one brown dwarf (Gl 229B: the first one to be discovered; Nakajima et al., 1995) in a combined sample of over 340 stars and a combined separation range of 10–1200 AU. This result is in stark contrast both with the frequency of RV extra-solar planets within 3 AU (5–15%; Marcy & Butler, 2000; Fischer et al., 2002) and with the frequency of stellar companions to stars over 10–1200 AU (9–13% for M–G-dwarf primaries; Fischer & Marcy, 1992; Duquennoy & Mayor, 1991). Analogous reasoning has prompted McCarthy & Zuckerman (2004) to conclude that the brown-dwarf desert extends much beyond the 0–5 AU probed by RV surveys. More recent results from other, smaller efforts, have been mixed, with surveys performed with more sensitive instrumentation generally reporting higher, though statistically not inconsistent, rates of success (e.g., 1 out of 50).

This situation is reminiscent of the initial search for sub-stellar companions through the RV method, both in the amount of effort invested world-wide and in the frustratingly low yield. However, the sensitivity of modern precision RV surveys has much surpassed the brown-dwarf mass regime, whereas imaging efforts are still mostly limited to intermediate and high-mass brown dwarfs. The RV brown-dwarf desert has remained nearly void even after the discovery of lower-mass extra-solar planets. Will this be the case with the direct imaging brown-dwarf desert?

The problem can be most comprehensively addressed in the context of Sun-like stars, because of the large body of empirical data that exist on the stellar and sub-stellar multiplicity of solar analogs. One one hand, the exhaustive low-precision RV and direct imaging study of stellar companions to G-dwarfs by Duquennoy & Mayor (1991) found that the peak of the stellar companion semi-major axis distribution occurs near 35 AU. Duquennoy & Mayor also found that the distribution of the mass ratios $q \equiv M_1/M2$ in binary systems is nearly flat over $0.0 < q \leq 0.4$. This result, further confirmed in more recent studies (e.g., Mazeh et al., 2003), indicates that systems with sub-stellar secondaries, i.e., the ones that comprise the lowest mass ratio ($q \leq 0.1$) bin, may not be much less common than systems with low-mass stellar secondaries. Although the data for the $q \leq 0.1$ bin in these multiplicity studies were largely (Mazeh et al., 2003), or entirely (Duquennoy & Mayor, 1991), extrapolated from higher mass-ration bins because of the severe incompleteness to low-mass companions, it appears plausible

[6] Another technique for detecting sub-stellar companions to stars is by astrometric, rather than spectroscopic (as in the RV approach), measurement of the stellar reflex motion. Similarly to the direct imaging approach, the astrometric technique is more sensitive to companions in wider orbits. Because, like the RV method, the astrometric technique also relies on the detection of orbital motion, it requires longer monitoring periods to probe the wider orbital separations. As a result, no extra-solar planets have been discovered from astrometric monitoring yet, though the first brown-dwarf companion was announced recently in Pravdo et al. (2005).

that more sensitive studies will detect significant numbers of widely-separated (tens of AU) sub-stellar secondaries.

On the other hand, precision RV surveys for much lower mass companions to Sun-like stars have found that the frequency of extra-solar planets rises with semi-major axis out to the completeness limit of the surveys ($\sim$3 AU; Marcy et al., 2003; Udry et al., 2003). This suggests that planetary-mass companions to stars may be even more common at even wider orbital separations. In addition, the last three years have seen the announcement of a number of RV "super-planets," objects with minimum masses in the 9–25 $M_{\rm Jup}$ range, at semi-major axes $>$1.5 AU (Fischer et al., 2001; Udry et al., 2002; Jones et al., 2002; Fischer et al., 2002; Vogt et al., 2002; Tinney et al., 2003; Endl et al., 2004). These likely brown dwarfs, residing at the outskirts of the RV brown-dwarf desert, are part of a more general positive correlation between mass and period for RV planets (Zucker & Mazeh, 2002; Udry et al., 2003), indicating that sub-stellar objects in even wider orbits may be even more massive.

Connecting the above lines of evidence for stellar and planetary companions to Sun-like stars, there is a strong indication that brown dwarfs, given their intermediate masses between those of stars and extra-solar planets, may exist with appreciable frequency in wide orbits around solar type primaries. *What fraction of Sun-like stars have such widely-separated brown-dwarf secondaries?*

This is the principle question guiding the present investigation. By undertaking a large direct imaging study of a carefully-selected sample of solar analogs, and by employing the modern high-contrast imaging capabilities of the Palomar 5 m and Keck 10 m telescopes, we are able to resolve the issue at a sufficient level of confidence.

Direct imaging investigations of sub-stellar multiplicity are also relevant to the study of the photospheric evolution of sub-stellar objects: both brown dwarfs and giant planets. As mentioned in §1.1, sub-stellar objects never go through a star-like main-sequence phase of constant luminosity and effective temperature. Instead, their luminosities and effective temperatures are strongly age-dependent. With the ages of field brown dwarfs still practically indeterminable, theoretical brown-dwarf cooling models have had few empirical constraints beyond the late-M to early-L spectral types of brown dwarfs found in young open clusters. Of strong interest, for example, is more accurate understanding of the transition between late L and early T dwarfs: a phenomenon occurring at approximately constant temperature ($\sim$1300–1500 K; Ackerman & Marley, 2001; Tsuji, 2002) but during which the near-IR $J - K_S$ color of a brown dwarf changes by more than a magnitude (Kirkpatrick et al., 1999; Burgasser et al., 2002). No brown dwarfs later than L7 have been age-dated yet, as none have been confirmed in open clusters or as companions to stars of known age. The discovery of such late-type brown dwarfs as companions to stars with known ages can provide much-needed empirical calibration and theoretical constraints. This is a second issue that will be addressed in the near future as a result of the present survey. At an age of 400 Myr and a photometrically-estimated spectral type of T0, one of the newly-discovered brown-dwarf companions is likely the first known young L/T transition object.

Going beyond the concrete goal to test the existence of the brown-dwarf desert at wide separations, imaging studies of the multiplicity fraction and separation distribution of low mass ratio ($q < 0.1$) binaries provide important clues for the mechanism of their formation and dynamical stability (e.g., Close et al., 2003). By virtue of being optimized for the detection of sub-stellar companions, the present survey provides ample material for future investigations of low mass ratio systems.

1.3 Observational Challenges and Constraints

The main challenge in direct imaging of sub-stellar companions to stars is achieving sufficient imaging contrast to detect a faint companion in the vicinity of its orders of magnitude brighter host star. Three main factors, addressed in turn below, contribute to this problem: attainable contrast, heliocentric distance to the star, and stellar youth.

Seeing-limited observations through the Earth's turbulent atmosphere suffer from the large extent ($1''$) of the imaging point-spread function (PSF). The contrast achieved in seeing-limited imaging is too poor to detect almost any sub-stellar companions within $\sim 10''$ from solar analogs (e.g., 100 AU from a star at 10 pc). This problem has been alleviated over the past decade by the availability of space-based imaging with the *Hubble Space Telescope (HST)* and of ground-based adaptive optics (AO)—a technique that compensates for atmospheric turbulence through the use of high operational frequency corrective optics. Large AO-equipped telescopes nowadays routinely produce diffraction-limited PSFs, with widths of order 0.05–0.10$''$ on 5–10 m class telescopes in the near-IR. Such angular resolution rivals that obtained by the *HST* and allows unprecedented scrutiny of small angular scales. The contrast achieved by various AO systems and the *HST* is generally $10^3 - 10^5$ at $1''$ from bright stars in the near-IR (1–2.5 μm)–far superior than the contrast of seeing-limited observations at the same angular separation (of order unity). However, AO is strongly limited by the need of the corrective system for a sufficiently bright nearby ($\lesssim 60''$) beacon, a "guide star," above the turbulent layers in the atmosphere to probe the distortion of the incident radiation. Without the use of an artificial guide star (a laser beam), the celestial distribution of bright natural guide stars (NGSs) allows the use of AO for only $\lesssim$1% of the total area of the sky. Fortunately, solar analogs within $\sim$200 pc are generally sufficiently bright to be used as NGSs themselves, thus allowing full use of the power of NGS AO for the present study.

The apparent angular scale of a stellar system is inversely proportional to its heliocentric distance: systems that are farther away are more challenging to resolve. Given an interest in imaging orbital separations of solar-system scales around other stars, we are limited in choice to relatively nearby stars, within 400 pc (40 AU at 0.1$''$ resolution). Furthermore, because of the inverse-squared dependence of flux on heliocentric distance, sub-stellar objects in faraway systems may be too faint to detect. In contrast-limited imaging, however, this factor is of lesser importance.

The contrast attained with AO or with the *HST* may still be inadequate to detect any but the most massive sub-stellar companions in intrinsic light, and is $\sim$3–5 orders of magnitudes too poor to detect companions in reflected light. As the detection of intrinsic light offers a clear advantage at this contrast level, we will discuss only this approach. While stars maintain a constant brightness throughout their hydrogen-burning lifetime on the main sequence, sub-stellar objects cool and get intrinsically fainter with age (§1.1). Hence, the brightness ratio between the primary star and the secondary sub-stellar companion progressively increases with time. Results from theoretical models of sub-stellar cooling (Burrows et al., 1997; Chabrier et al., 2000) indicate that, at an imaging contrast of 10^4, a stellar/sub-stellar binary with a solar analog as the primary needs to be younger than $\approx$3 Gyr (the Sun is 4.56 Gyr old) to have a 70 $M_{\rm Jup}$ companion detectable, and younger than $\approx$20 Myr to have a 10 $M_{\rm Jup}$ companion detectable (cf. Fig. 1.1). Therefore, searches for sub-stellar companions to young ($\lesssim$1 Gyr) stars will be expected to be more sensitive to sub-stellar masses than searches around older (1–10 Gyr) stars. Unfortunately, stellar age is not a direct observable, and is an elusive quantity to