Brown Dwarfs
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Companions to Young Stars

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Abstract. Brown dwarfs occupy the important region in the mass range between stars and planets. Their existence, ambiguous until only recently, and their properties give insight into stellar and planetary formation. We present statistical results of an infrared, coronagraphic survey of young, nearby stars that includes probable companions to three young G-type stars, Gl 503.2 (G2V), HD 102982 (G3V), and Gl 577 (G5V). The companion to Gl 577 is a possible binary brown dwarf, according to evolutionary models. A dynamical determination of the components' masses will be achievable in the near future and will provide an excellent test of the predictive ability of the evolutionary models.

1. Introduction

To fully explore the similarities and differences between stellar and planetary formation, the study of brown dwarfs as companions is essential. Since the primary's age and distance have been determined, these two properties, usually uncertain for field brown dwarfs, are already known. The primary goal of this survey of 45 young (t<300Myr), nearby (d<50pc) stars was the discovery of substellar companions. Because substellar objects are hotter and brighter when younger, they can be more easily detected. Each target star was selected based on its being single and having at least two youth criteria (chromospheric activity, lithium, proper motion) indicating a young age. The final sample had a median age of 150 Myr and a median distance of 30 pc. The survey utilized the infrared coronagraph on the Near-Infrared Camera and Multi-Object Spectrometer (NICMOS) on the Hubble Space Telescope (HST). Earlier results include the brown dwarf companions TWA5B (Lowrance et al 1999; L99) and HR 7329B (Lowrance et al 2000).

2. Observations with NICMOS on the Hubble Space Telescope

The observing strategy was to place each star behind the coronagraph, observe for approximately 800s, roll the telescope by 30 degrees, and observe again for 800s (actual integration times were adjusted to fit in variable orbit times). Following the method fully described in L99, when we subtract the two images, a positive and negative image of any candidate companion should remain.

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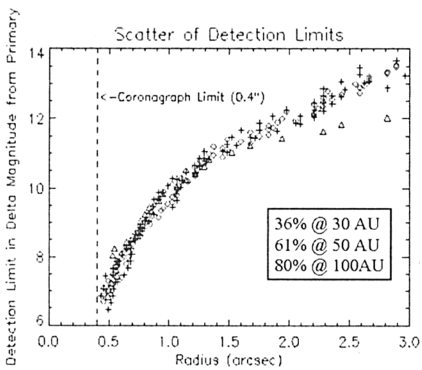

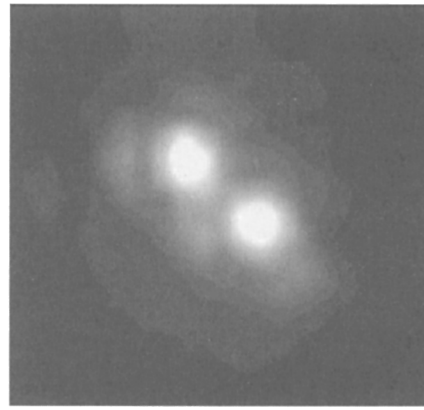

Figure 1. (a)Detection limits reached in survey of young stars. Inset box indicates percentage of objects around which a 5 $M_{Jupiter}$ object would have been detected. Different symbols indicate the different brightness of the primary star plotted; diamonds for H=5 mag to triangles for H=9 mag.(b) The Adaptive Optics image of the companions to Gl 577A, clearly indicating a binary companion with separation $0.082'' \pm 0.005$ that corresponds to <4 AU at that distance.

3. Determining Detection Limits

To determine our sensitivity limits within the NICMOS roll-subtracted images of the observed stars, we planted[1] point-spread-function (PSF) stars, generated with Tiny Tim (Krist & Hook 1997), at random locations in every image. These PSF stars are noiseless, can be adjusted in flux, and were stepped by 0.2 mag to examine a range of magnitudes from H=10–22 for each subtraction.

In figure 1, we plot the detection limits found overall in the observations. Our sample has an average primary magnitude H = 7 mag and a median age of 0.15 Gyr. At $1''$, we can detect ΔH=9.5 mag for all stars. At a median distance of 30 pc, $1''$=30AU and our average limit corresponds to $M_H = 14.1$ mag. From models (Burrows, A., personal communication), this corresponds to less than 20 $M_{Jupiter}$ for the median age.

This program fully sampled 45 young stars with the ability to detect 30 $M_{Jupiter}$ brown dwarfs at 0.5 $''$. For some separations from the primary, we were able to detect objects into the high mass planet range. For our oldest stars, t=0.3 Gyr, a 5 $M_{Jupiter}$ object is expected to have a absolute H mag of 18.7 mag (Burrows, A., personal communication). Closer than $5''$, detectability depends on the brightness, age, and distance of the primary. We find that a 5 $M_{Jupiter}$ object could have been detected around 61% of the primaries at 50AU (Figure 1a), approximately the outer edge of the solar system.

[1]Software courtesy of A. Ghez and A. Weinberger.

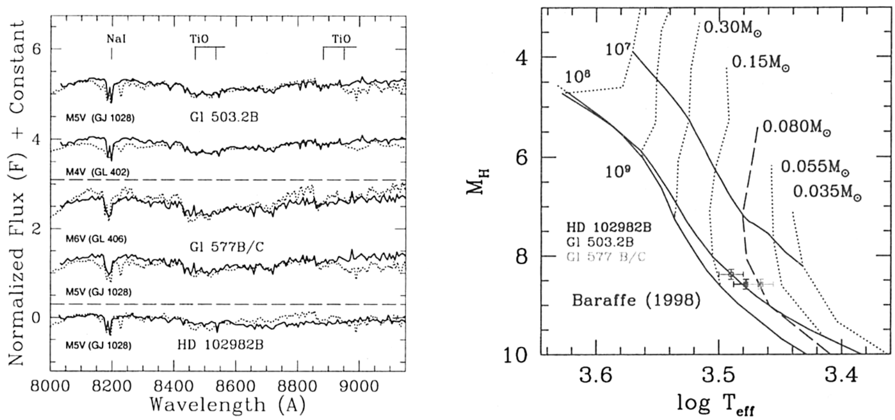

Figure 2. (a)STIS spectra of HD 102982, Gl 577B/C, and Gl 503.2B (solid) (normalized from ergs/s/cm^2/Å) separated by the dashed lines, compared with standard late-type M dwarf spectra (dotted) (Kirkpatrick et al. 1991;Kirkpatrick et al. 1997). The zero level of each spectrum is -1.2, 0, 1.3, 2.7 and 4 respectively) (b)Evolutionary diagrams with all three companions to the G stars. The derived ages of the secondaries match the primaries' ages implied from youth criteria. The binarity of Gl 577 B/C has been taken into account, and it lies on the stellar/substellar boundary.

4. Follow-up Observations of Candidate Companions

We followed up the candidate companions to Gl 503.2, HD 102982, and Gl 577 with spectra from the HST Space Telescope Imaging Spectrograph (STIS) and using Adaptive Optics (AO) imaging at several ground-based telescopes.

All three secondaries were observed with the STIS. Each primary was acquired into the 52″×0.″2 slit and offset based on the NICMOS astrometric results to place the secondary into the slit. Spectral imaging sequences were completed in one orbit per star with the G750M grating in three tilt settings executing a two position dither along the slit at each.

The STIS spectra were calibrated, averaged, binned to a resolution of $\sim$ 6Å, and normalized to the flux (in ergs/s/cm^2/Å) at 8500Å. We compared the final spectra to those of standard star spectra (see Figure 2a). The best fit appears to lie between M4V and M5V for Gl 503.2B, between M5V and M6V for Gl577B/C and M5V for HD 102982B.

The Gl 577 and Gl 503.2 systems were observed with the Canada-France-Hawaii telescope (CFHT) on March 4 and 5, 1999 (UT) using the AO system PUEO (Rigaut et al. 1998) and with the 200 inch Hale telescope at Palomar Observatory on May 14, 2000 (UT) using the AO system PALAO. The Gl 577 system was also observed on 12 Aug 2000 using the AO system on the 10-m W.M. Keck II telescope (Wizinowich et al. 2000) with the slit-viewing camera (SCAM) on NIRSPEC (McLean et al. 1998). Basic reduction included correction for bad pixels and flat-fielding procedures.

A common proper motion between the primaries and secondaries was established. Both the Gl 577A and Gl 503.2A proper motions have been measured accurately by the Hipparcos (Perryman et al. 1997) satellite. The proper motion for HD 102982 is listed in the Tycho catalogue (Hog et al. 2000). From adaptive optics observations, the Gl 577 and Gl 503.2 systems were each measured three times. The HD 102982 system was measured in the STIS observation. All were within 1 sigma of the previously measured separation and 3 sigma outside the predicted separation from proper motion. We therefore conclude that Gl 503.2B, HD 102982B, Gl 577B/C are companions to the brighter primaries.

5. Derived Mass and Age

From their placement on pre-main sequence evolutionary tracks (Baraffe et al. 1998), we can infer a mass for the secondaries (Figure 2b). HD 102982B and Gl 503.2B appear to be consistent with 100 Myr low-mass (< 0.15 $M_\odot$) stars. Gl 577 B/C appear to lie at the theoretical stellar/substellar border mass of 0.08 $M_\odot$ from the infrared magnitude and spectral type. Both components are of equal magnitude, so both might be brown dwarfs.

There are very few stars of mass < 0.2 $M_\odot$ with a dynamical determination of their mass, as few short-period binaries in this mass range are resolved. High spatial resolution provided by HST and adaptive optics now makes it possible to resolve fainter binaries with smaller separations and shorter periods. With a separation of only $\sim$4 AU, a dynamical mass for Gl 577BC can be determined in less than a decade. Only then will the predictive ability of evolutionary models be tested near the stellar/substellar boundary. Further infrared adaptive optics observations along with radial velocity measurements are currently underway.

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