Imaging and Spectroscopy of Hot (Young) "Ultracool" Companions

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Abstract. We report the initial results from a program of HST/STIS spectroscopy of "hot" low-mass (brown dwarf) companions to nearby young stars identified in our HST/NICMOS coronagraphic imaging survey. We present spectra of the likely 20 and 40 Jupiter mass companions to CD -33° 7795 and HR 7329, respectively, the binary companions to GL 577 (both, possibly, brown dwarfs), and the low-mass star GL 503.2B. We discuss the state of our recent follow-up observations of the putative companion to TWA 6. We add these companions to the very few already known, allowing the first steps to be taken toward answering many fundamental questions regarding the formation and evolution of multiple systems with components near and below the stellar/substellar boundary.

1 Introduction

The discovery and subsequent characterization of sub-stellar objects in stellar systems continues to be one of the key goals of contemporary observational astronomy. From the low-mass end of the mass-luminosity function (which is still very poorly constrained for $M_* < 0.2 M_\odot$) through the regime of brown dwarfs and into the domain of giant planets, the near and sub-stellar bestiary remains fertile ground for exploration. Knowledge of stellar and sub-stellar masses and luminosities at and below the $\sim$0.08 $M_\odot$ H-burning limit is of fundamental importance in many inter-related areas such as the determination of the stellar mass function at the low-mass "end" of the main sequence, the theory of stellar evolution, the resolution of age/evolution issues and the origins of stellar and planetary systems. Yet, for *companions*, the transition region between very low-mass stars and giant planets is poorly understood and ill-observed (due in large part to their intrinsic faintness and close proximities to their primaries).

With the discovery and imaging of the brown dwarf companion to GL 229 [24], the very existence of such objects moved them from the realm of conjecture to observation. And, since the first detection of an extra-solar planet in the Jovian-mass regime, the companion to 51 Peg [21], continuing discoveries of 1–10 Jupiter mass companions to solar-like stars by indirect methods have revealed an unanticipated diversity in mass ranges, dynamical properties, and primary-star characteristics [19].

These radial velocity surveys suggest that $\sim 5\%$ of main-sequence stars possess 0.5-8 Jupiter-mass companions at distances typically < 3AU from their primaries, but $<1\%$ of these stars have brown dwarf companions. (e.g., [20]). Speculations as to the cause of this "brown dwarf desert" (e.g., [11]) may be observationally biased as these surveys are currently insensitive to higher mass objects at distances from tens to hundreds of AUs because temporal baselines of decades to centuries are required to detect them.

Recently, however, many isolated "field" brown dwarfs have been discovered from large ground-based surveys such as the 2-Micron All-Sky and Sloan Digital Sky surveys and subsequently confirmed spectroscopically ([13]; [9]). And, brown dwarfs (or "free floating planets") have been turning up in proliferation in very young clusters associated with star-forming regions (e.g., [18]; [23]). Indeed, population statistics in both the field and young clusters suggest that single brown dwarfs, once considered somewhat exotic objects, may be as common as stars (e.g., [33]; [10]). Yet, the *companion* mass and number fractions of substellar objects, which occupy a niche in the mass function between stars and planets, remain essentially unknown. How common are they? Only a few brown dwarf companions to stars have thus far been found and confirmed ([26]; [5]; [16]). The disparity may simply be a contemporary observational selection effect, or the formation processes for field vs. companion brown dwarfs may be intrinsically very different. Does the star formation process end abruptly for masses below the H-burning limit in multiple systems? Do companion brown dwarfs form in processes more like planets than stars (i.e., fragmentation vs. core collapse; e.g., [4])? And, how might the presence of a brown dwarf companion effect the evolution of a newly-forming solar system?

The unequivocal identification and characterization of companion substellar objects in young stellar systems not only helps to enumerate the population statistics, but will ultimately lead to follow-up dynamical astrometric studies to ascertain their masses directly and unambiguously. Though many such objects will have to be discovered and studied before questions such as those posited above are fully answered, with those now in hand we have a logical starting point to begin investigating the intriguing possibilities.

2 Observations

Long before the adoption of NASA's *Origins* theme, which contains in its foundation the establishment of scientific activities to investigate the birth and early evolution of stars and planets [8], the NICMOS Instrument Definition Team embraced these goals in formulating our Environments of Nearby Stars (EONS) program. A cornerstone of our EONS investigations was a systematic search for previously unknown low-mass candidate companions to young and nearby stars. Carried out during HST Cycle 7, this survey was designed to find companion candidates spanning two decades in the mass-spectrum down into the regime of Jovian mass planets (for objects as young as $\sim$ 10 Myr). Using the Near-Infrared Camera and Multi-Object Spectrometer (NICMOS) on the Hubble Space Telescope (HST) we conducted a coronagraphic imaging survey of young and nearby stars searching for, and finding, candidate brown dwarf and giant planet companions. We have now confirmed the physical association of a subset of those objects through the establishment of common proper motions of the candidates with their putative primaries. Further, we have determined their spectral types and photospheric temperatures using near-IR/optical spectra obtained with the Space Telescope Imaging Spectrograph (STIS).

2.1 NICMOS Imaging - Detection

Approximately $\sim$ 18% of the NICMOS IDT's observing time on HST was dedicated to NICMOS/EONS survey, as previously discussed in detail in the literature ([27], [14], [29]). In summary, we coronagraphically imaged the circumstellar regions of eighty-three young and nearby stars, primarily in H-band. In particular we observed:

1) Thirty-eight very young main-sequence stars with mean distances of $\sim$30pc. Young sub-stellar companions will still be in a higher luminosity phase and thus more readily detectable. The median age for our candidates with well-established ages is $\sim$ 90Myrs with 8 candidates as young, or younger than, 10Myrs. This sample including several members of the TW Hydrae association (d $\sim$ 55pc), the nearest site of recent star-formation to the Earth [12].

2) Twenty-seven M-dwarfs which are a) very nearby (d $<$ 6pc), with spectral types later than $\sim$M3.5; b) young (age $<$ 10 Myr) and (d $<$ 25 pc); and c) spectrally the latest known (i.e., “ultra-cool” dwarfs later than $\sim$M8.5).

3) Eighteen primarily main-sequence stars with large IRAS excesses and other indicators of dust, to image circumstellar material at 1.1 and/or 1.6μm.

Each target was observed in a single orbit (providing a total of $\sim$ 25 minutes of integration time), but at two different spacecraft orientation angles to permit the discrimination of point spread function artifacts from intrinsic circumstellar sources. By subtracting two coronagraphically occulted images of a star, rolled about the target axis, the NICMOS/HST system can achieve a per-pixel reduction in background intensity approaching 10^{-6} of the peak stellar intensity at a distance of 1”. In H-band this allowed us to achieve statistically significant detections of companions as faint as H $\sim$ 24, 10–15 magnitudes fainter than their primaries at separations of 0.5”–3.0” [28]. For the youngest objects in our sample these levels of performance enable the imaging of “hot” Jupiters at distances of tens of AUs from their primaries. Typically, the stability of the instrumental system allows us to determine the positions of coronagraphically imaged putative companions with a precision of about 10mas with respect to their suspected primaries in unocculted target acquisition images, establishing an astrometric baseline for follow-up observations.

2.2 Ground-Based (AO) Imaging - Confirmation

The unequivocal determination of companionship for a candidate rests in the confirmation of physical association with its putative primary through the establishment of common proper motions. A subset of our targets, those with less severe contrast ratios and/or larger separations, are observable with ground-based adaptive optics systems. With our first-epoch NICMOS observations, and later ground-based AO imaging which we are obtaining on the Palomar, Keck, and CFHT AO systems (for those observationally possible), we are able to discriminate against background objects for many of these targets on relatively short time-scales. For several high proper motion objects such astrometric confirmation of companionship has already been secured. For four astrometrically confirmed objects, of six thus far also studied spectroscopically, we have found CD -33° 7795B, HR 7329B, and GL 577B/C to be brown dwarfs (the latter a brown-dwarf binary, the first such hierarchical companion found), and GL 503.2B to be a very-low-mass star near the stellar/brown dwarf boundary. The astrometric results for TWA 6"B", an extrasolar giant planet (EJP) candidate, are indeterminate at this time, as a longer temporal baseline is required to confirm or reject its companionship.

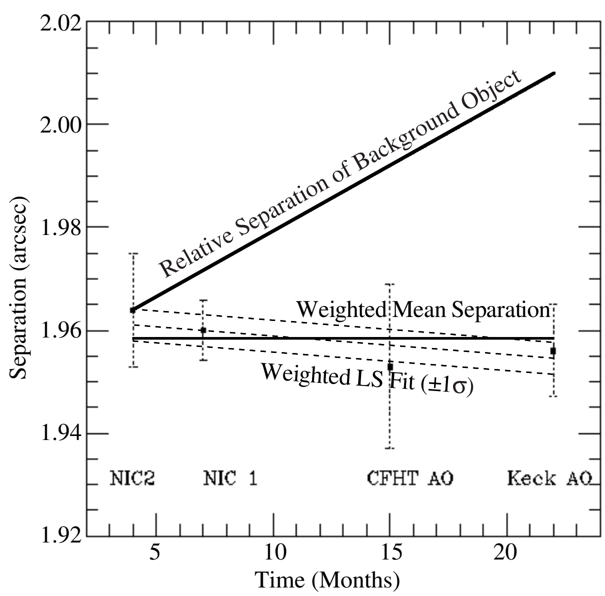

Fig. 1. Companionship is confirmed (or rejected) by differential proper motions. As an example we show angular separation measures for CD -33° 7795A/B over an 18 month baseline which, statistically, remained constant (within the measurement error). We compare this with the anticipated change in separation from the proper motion of CD -33° 7795A if the companion was actually background star, and conclude they are indeed a common proper motion pair.

2.3 STIS Spectroscopy - Characterization

During HST Cycle 8 we obtained STIS spectra for a subset of our young (less than $\sim$ 0.3 Gyr) NICMOS candidate companions to obtain their spectral types and effective temperatures. The instrumental characteristics of STIS+HST are uniquely suited to the task of characterizing the substellar nature of these targets. The ability of STIS to obtain spectra in the regions of key atomic lines and molecular bands to differentiate between very low mass stars, brown dwarfs, and extra-solar giant planets, for very faint companions in close angular proximity to their bright primaries, is unmatched by any current ground-based capabilities. Representative spectra of two young objects CD -33° 7795B and HR 7329B, in

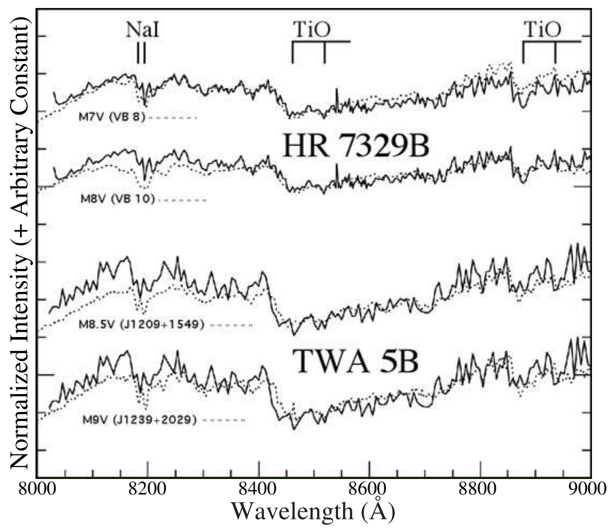

Fig. 2. Young, and therefore hot, brown dwarfs have spectra resembling M dwarf stars of the same photospheric temperatures, rather than exhibiting spectral characteristics of older L and T dwarfs. Here we compare our STIS spectra of TWA 5B (CD -33° 7795B)and HR 7329B, both presumed to be one to a few x 10^7 yrs of age, with several M stars. We ascertain their spectral types on the basis of the continuum, the strength of the NaII doublet, and the depths of the TiO band-heads.

the 8000–9000Å range, are compared to several late M-dwarf standards of similar effective temperatures in Figure 2. In the case of CD -33° 7795B we find a very good fit for M9V, and an effective temperature of 2600K. For HR 7329B we deduce a spectral class of M7.5V, and effective temperature of 2700K. STIS spectra in $\sim$ 7500–9500Å range allow us to compare the strengths and morphologies of diagnostic spectral tracers in late M, L, and T dwarfs (and giant planets). Young, and therefore hot, brown dwarfs have spectra resembling M dwarf stars of the same photospheric temperatures. In this spectral region, M dwarfs are dominated by bands of TiO and, for the latest M dwarfs, VO. For cooler L-types, the oxide molecules disappear onto grains, leaving cleaner spectra showing only bands of the hydride molecules CrH 8611Å and FeH 8692Å along with sharp atomic lines of the alkali metals Na 8183 & 8195Å, Rb 7800 & 7948 Å, and Cs 8521 & 8943Å. In the spectra of the T class, which abut the L dwarfs in temperature, the hydrides have disappeared onto grains and some of the alkali metals have formed into chloride compounds, leaving Rb and Cs lines (as in GL 229B) and, for cooler spectra, CH_4 8890Å. H_2O vapor bands ($\sim$ 9300–9600Å), which gain strength throughout the sequence from late-M through the methane types, are significantly compromised in ground-based spectra due to atmospheric absorption (e.g., see figure 4 of [30]).

STIS target acquisition and dispersed spectral images also allow us to further constrain the relative proper motions of the presumed systemic components. For example, a spectrum was secured for HD 102982B [14] in the 0.2" wide slit, which would have failed for most possible geometries if it was a background object. Conversely, in the case of HD 177996 companionship for the candidate was rejected as the object did not appear in the slit (because of its differential proper motion as a background star) after the "primary" was successfully acquired.

3 Hot Brown Dwarf Companions

While the spectra of objects like CD -33° 7795B and HR 7329B clearly resemble late M dwarfs, their youth belies their true nature - "hot" brown dwarfs. A fundamental, and reasonable, assumption is that the low-mass companions are coeval with their primaries. With effective temperatures determined from our spectra, and bolometric magnitudes derived from our H-band imaging, we can then place the companions on H-R diagrams demanding coevality with their primaries, and estimate their masses through evolutionary cooling models.

3.1 CD -33° 7795 (TWA 5)

CD -33° 7795A, an M1.5 dwarf (H=7.2) is a member of the member of TW Hydrae Association [12]. With an estimated age of 10 Myrs ([12]; [32]) the primary exhibits X-ray and H-α emission, and strong Li absorption. CD -33° 7795 was a suggested spectroscopic binary, so chromospheric activity may be enhanced [3], but its space motions and Li absorption are consistent with other TW Hydrae association members. Keck AO imaging resolved the primary as a close ($\sim$ 0.06") binary with nearly-equal magnitude components (see Fig. 3). The close binary orbit must be in a nearly edge-on, however, as it was unresolved at the time of the NICMOS observations.

CD -33° 7795B was the first brown dwarf companion candidate identified in the NICMOS survey [15], and co-discovered by [34] in speckle observations taken at the NASA IRTF. An H=12.14 magnitude companion to TWA 5A (ΔH=4.92) was readily seen in the NICMOS F160W (1.6μm) coronagraphic difference image with a separation of 1.96" ($\sim$ 110 AU projected distance) at a PA of 358.9°. Near-IR colors were measured from KeckII/LRIS acquisition imaging, possible given the modest primary/secondary contrast ratio and sufficiently large separation. Differential astrometric measures from HST/NICMOS, CFHT AO and Keck AO

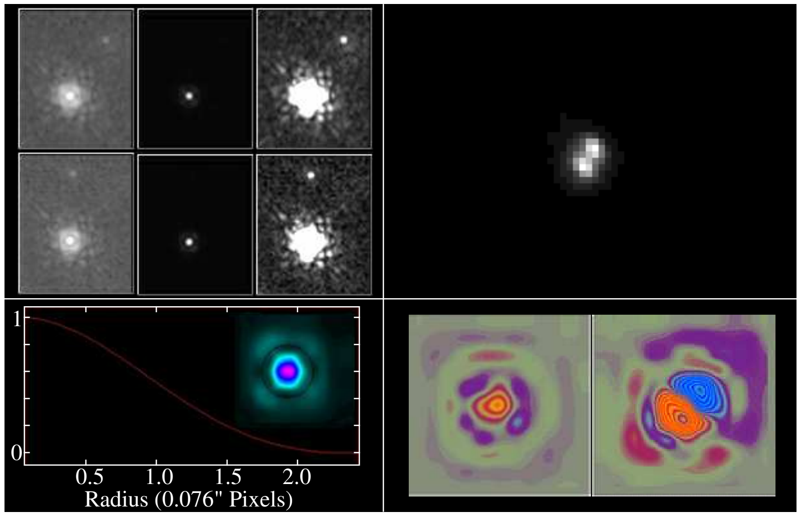

Fig. 3. Direct imaging of CD -33° 7795A. Top Left - NICMOS 1.65μm target acquisition (TA) images at two spacecraft orientations (three stretches to show PSFs of A and B components). Top Right - Keck 1.6μm AO image, 22 months later, revealing the primary as two equal magnitude components separated by 60mas. Bottom Left - Combined NICMOS TA image and radial profile of A component shows no evidence of duplicity. Bottom right - PSF core of A component fell at different sub-pixel locations in the two rolled NICMOS TA images. Difference of the two TA images (left), stretched to show residuals from imperfect subtraction, bears no resemblance to the difference image of two equal magnitude point sources separated by 60mas (right).

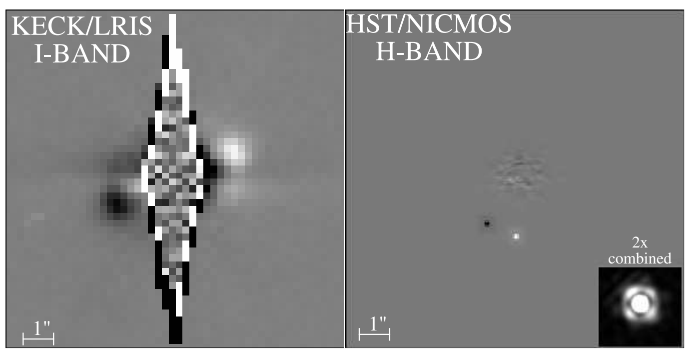

Fig. 4. Left - Keck/LRIS I-band image of CD -33° 7795, self-subtracted after 180° image rotation shows (positive and negative) images of B component. Right - NICMOS H-band coronagraphic images CD -33° 7795B, spacecraft target point rolled around component A and subtracted. Inset - positive and negative image conjugates from subtraction combined.

images over a baseline of 18 months confirmed companionship for the secondary through common proper motions (see Fig. 1). From the NICMOS and Keck photometry, and a bolometric correction of BC(H) = 2.8, we ascertained its luminosity as 0.0021 $L_\odot$ and its effective temperature as $\sim$ 2600K. From these measures we determined a photometric spectral classification of M8.5V ($\pm$ 0.5 spectral class). These results were confirmed by the STIS spectra (see Fig. 2), though a better fit to the template spectra is obtained at M9V (still within the estimated photometric uncertainty). Recently [25] obtained lower resolution spectra using FORS2 on the VLT which are in agreement with these results.

3.2 HR 7329

HR 7329A, a member of the recently discovered Tucanae association [35] is of comparable distance (d = 47.61 $\pm$ 1.6pc as determined by the Hipparcos mission) and age as CD -33° 7795. Though somewhat uncertain, it is likely to be 10–30 Myr, based upon its location on a HR diagram, very large Vsini (330 km/sec; [1]), and Tucanae association membership. A brown dwarf companion candidate was identified with NICMOS, in close proximity to the H=5.05 A0V primary at an angular distance of 4.17" [16]. Again, assuming physical association for the unresolved object (196 AU projected distance), the H=11.90 companion candidate at PA of 166.8° was estimated to have a luminosity of 0.0026 $L_\odot$ (Habs = 8.54 with BC(H)=2.67).

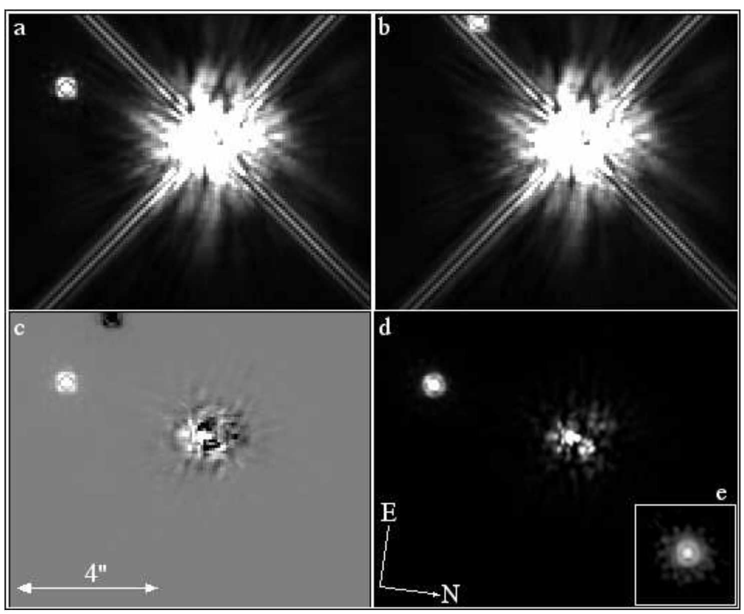

Fig. 5. Top (a,b) - NICMOS coronagraphic images of HR 7329A & B. In panel (b) the companion PSF is partially off of the detector. (c) - Difference image (rolled 29.9° about primary component). (d) - Combined difference image conjugates. Inset (e) - Detailed recovery of roll combined PSF.

3.3 GL 577

While outside of the NICMOS coronagraphic aperture, a faint “extended” object was seen in two short NICMOS target acquisition images of the young star GL 577 [22] (H=6.88, G5V) at a distance of 5.35” (∼240 AU projected separation). Using the ∼50x brighter image of GL 577A as a reference PSF, the ”extended” object was nulled by two point sources differing by <15% in H-band brightness separated by ∼0.1”. The binary nature of this suspected companion was recently confirmed with follow-up imagery obtained with the PHARO adaptive optics camera on the Palomar 200” telescope [17]. Companionship (thus coevality) for the GL 577B/C pair was established by their common proper motions with GL 577A over the ∼ 2 year baseline since the NICMOS observation.

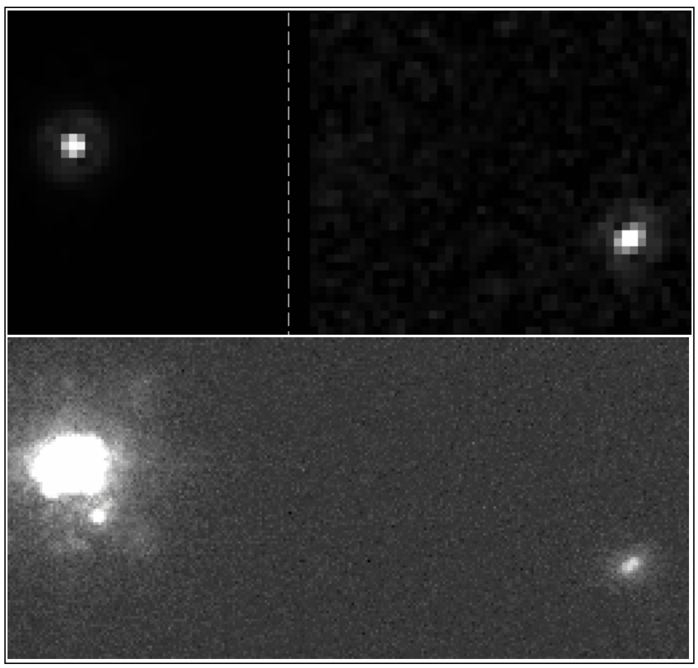

Fig. 6. Top - NICMOS TA image of GL 577A & B/C (flux renormalized x50 for B/C companions on right side of frame). Bottom - BOTTOM: Palomar 200” AO image (bright spot below-right of primary is a filter ghost).

A blended spectrum of GL 577B/C (see Fig. 7), recently obtained with STIS, resembles that of an M5.5V star. Differences in detail arising from the superposition of the individual spectra are noted and careful deblending of the spectra will be required to properly ascertain the spectral types and effective temperatures of the components. However, as both components are roughly equal in luminosity (derived from the spectral type, H magnitude and distance), and they each have effective spectral temperatures of ∼ 2900K.

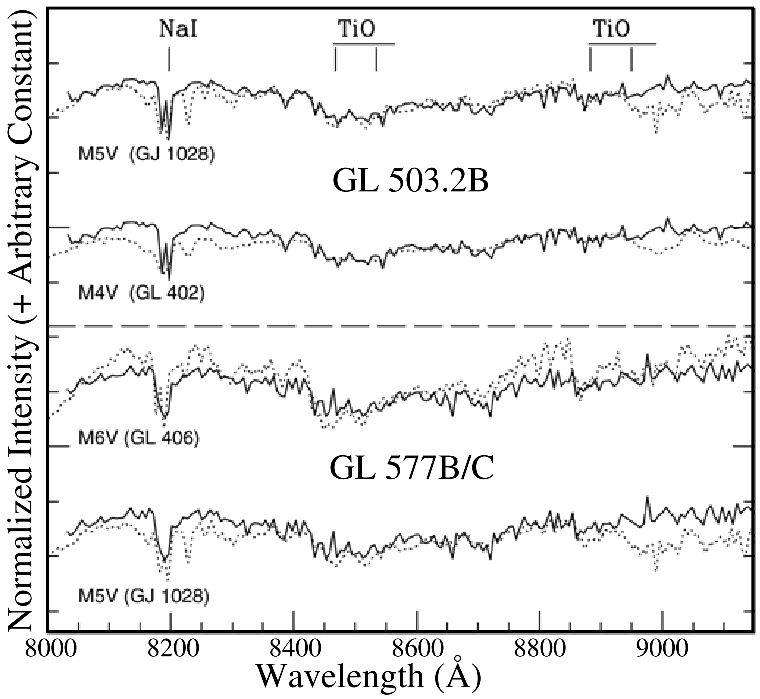

Fig. 7. Spectrum of GL 503.2B (top) and blended spectra of the B/C companions to GL 577 (bottom) compared to those of late M dwarfs (dotted lines). Effective photospheric temperatures of ∼ 3150K for GL 503.2 and ∼ 2900K for each component of ∼ 2900K is found.

3.4 Mass Estimates

Brown dwarfs cool as their luminosities decline with age, approximately as $L \sim M^{-2.24} T^{-1.3}$. Hence, mass estimates depend upon the efficacy of the age determinations, and of the details of cooling models themselves. For older stars determining the ages of the more massive primaries becomes more difficult and uncertain. Obtaining independent age estimates for the newly determined companions via, for example, Lithium abundance, will be a very important check and constraint for these mass estimates. In all cases considered here we currently rely on the ages determinations of the primaries.

Assuming coevality with their respective primaries, we place the companions on evolutionary tracks (e.g., Fig. 8) from [2], [6], and [7] to estimate their masses. For CD -33° 7795B we find a mass of ∼ 20 Jupiters, and for HR 7329B ∼ 40 Jupiters. In the case of GL 577B and C, we assume a B/C bolometric luminosity ratio of at most 1.15:1, implicating both as transitional objects, with one, and likely both brown dwarfs.

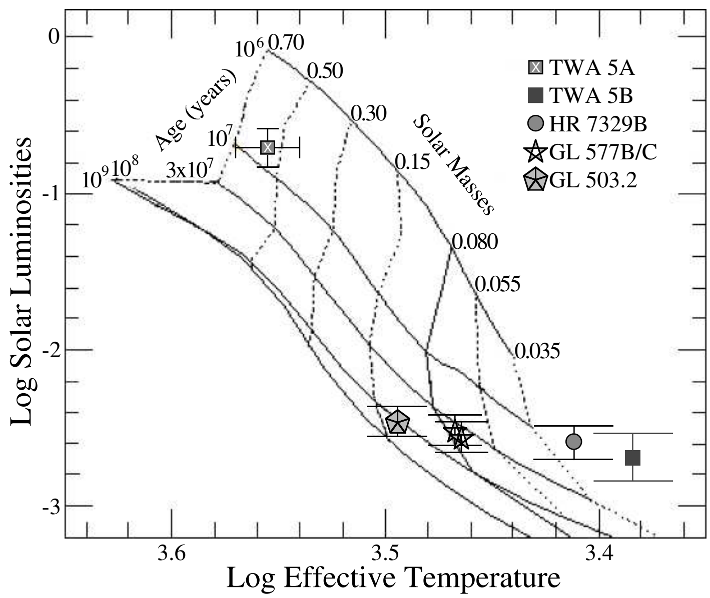

Fig. 8. Placement of companions on an H-R diagram and in the context of evolutionary isochrones of low-mass stars and substellar objects [2] based upon luminosities derived from NICMOS imaging and effective temperatures inferred from STIS spectra.

3.5 Low Mass, but Not Low Enough

With an estimated age of 300 Myrs for the H=5.45 solar-like (G2V) UMa group primary GL 503.2A (n(Li)=2.56, EW=77Å, vsini=25km/s; [31]), the $\sim$ M4.5V spectrum of its companion is indicative of a low mass star rather than a hot brown dwarf (Fig 7, top). Thus, we reject the possibility of the sub-stellar nature of this 1.56” distant companion (projected separation of 40 AU at d = 25.7 pc.) With an estimated effective temperature of 3150 $\pm$ 100K, we find the companion mass to be in the range of $\sim$ 0.1 to 0.15 solar masses.

4 Extrasolar Giant Planets?

4.1 Imaging

The feasibility of imaging young Jovian-mass planets by NICMOS coronagraphy was demonstrated with the acquisition of a S/N=50 1.6μm image of a candidate extra-solar giant planet companion to ROSAT 116 (H=6.9, K7V), also a member of the TW Hydrae association (TWA 6). The H=20.1 putative companion seen in Fig. 9 is 2.5" ($\sim$ 140 AU projected distance) from and 13.2 magnitudes fainter than TWA6. In a 0.9μm NICMOS camera 1 observation the object was not seen to a limiting magnitude of > 22, indicative of a very red source (if not a highly reddened background object). *If* the object is physically associated and coeval with ROSAT 116, its absolute H magnitude suggests an effective surface temperature of $\sim$ 800K (for a surface gravity of 7.5x10^4 cm^2 s^{-1}) and a mass of $\sim$ 1 Jupiter based upon evolutionary models updated from [6].

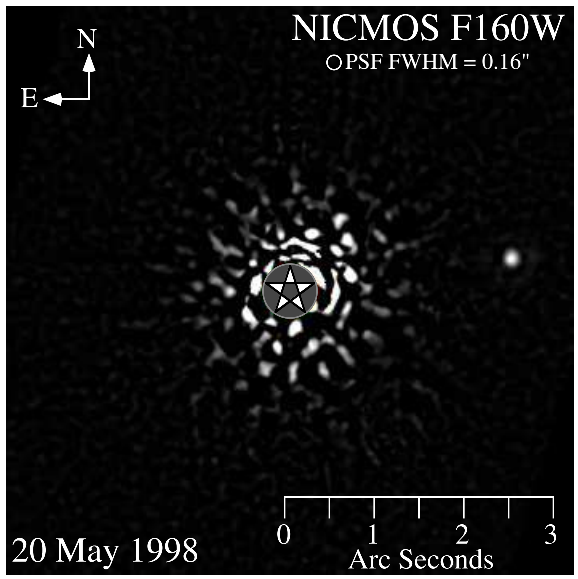

Fig. 9. An EJP companion *candidate* to ROSAT 116 (TWA 6) is readily seen in this NICMOS F160W coronagraphic image. Though the nature of the object is still to be determined, the viability of direct detection of young EJPs via NICMOS differential coronagraphy is demonstrated by this image.

We are attempting to use the Keck AO system to establish (or reject) the physical association of this candidate with TWA 6. Currently, with less than a two year baseline, the measurement errors in the relative proper motions are of the same order of magnitude as the proper motion of TWA 6 itself. Further astrometric calibration (and a longer temporal baseline) is required to improve the relative astrometry which, at the moment, is inconclusive.

4.2 Spectroscopy

Because of the extreme contrast ratios and close angular proximities of EJP companions, spectroscopy is much more of a challenge than imaging. We recently obtained a low resolution STIS spectrum of TWA 6'B' in six HST orbits. Not unexpectedly its faint spectrum is highly contaminated by the dispersed light of the much brighter primary, which is in close proximity to the slit. A "spray" of scattered light in between the companion spectrum from those arising from the diffraction spikes of the primary is due to instrumental scattering and diffraction effects. To date attempts at modeling and removing the background contamination have been only partially successful. Additional work is required to better understand the instrumental scattering and the limits imposed by the STIS optical system before a photometrically calibrated spectrum of the candidate object can be properly extracted. Scattered light calibration observations are scheduled for late 2000. Unfortunately, at this juncture, any interpretation would be premature.

5 Summary

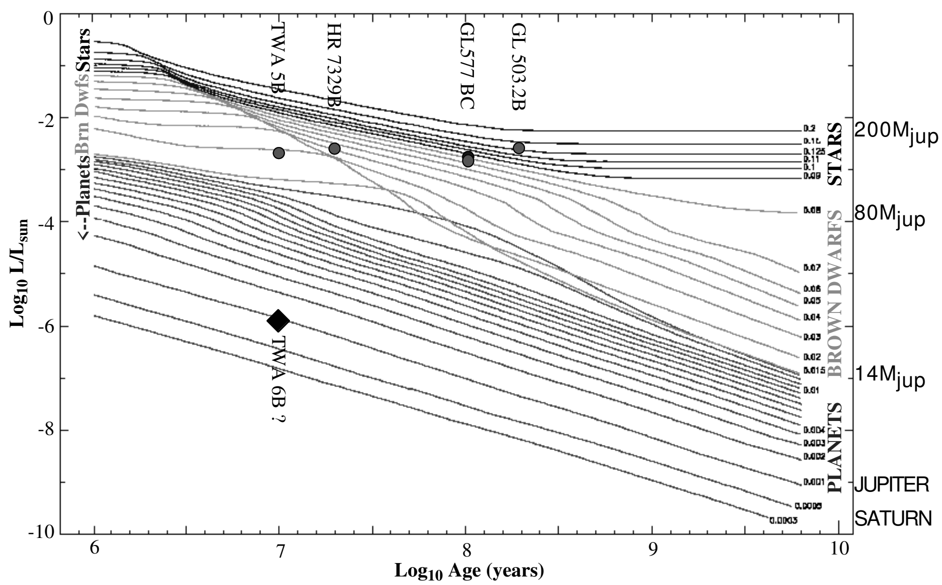

Fig. 10. With ages assumed from the characteristics of their primaries we estimate masses for the well-established companions observed spectroscopically with STIS (circles), based upon evolutionary cooling models for very low mass stars and substellar objects from [6]. The classification of "transitional" objects (such as GL 577B/C and possibly GL 503.2B), and the characterization of all objects during their cooling phases depends critically upon their presumed ages. Intrinsically fainter objects, such as the possible companion to TWA 6 (diamond) may be observed into the planetary-mass domain for objects of sufficient youth.

The NICMOS coronagraphic survey, follow-up ground-based AO imaging and STIS spectroscopy have given rise to the discovery, confirmation, and preliminary characterization of several very low-mass and sub-stellar companions. Here we have reported on the first results from this survey. Additional candidates identified by NICMOS are being followed up in a similar manner. By assuming coevality with their primaries we can estimate the masses of the companions through evolutionary cooling models (e.g., see Fig. 10, adapted from [6]). Age determinations of the primaries, however, are somewhat uncertain (particularly for the older stars in our sample). Hence, independent determinations of the ages of the companions (e.g., via Lithium abundance and H-α equivalent widths) is essential to better constrain the nature and properties of the newly discovered companions.

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