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Substellar Companions to Nearby Stars from NICMOS Surveys

Glenn Schneider

Steward Obs., U. Arizona, 933 N. Cherry Ave., Tucson, AZ 85721 USA

Eric E. Becklin & Patrick J. Lowrance

UCLA, 405 Hilgard Ave., Los Angeles, CA 90095 USA

Bradford A. Smith

U. Hawaii, 82-6012 Puuhonua Rd. Naoopoo, HI 96704 USA

and the NICMOS IDT/EONS and HST GO/8176 Teams

Abstract. A coronagraphic imaging survey of 65 nearby stars was conducted using the Near Infrared Camera and Multi-Object Spectrometer (NICMOS) on the Hubble Space Telescope by the Instrument Definition Team. Using these guaranteed time observations we searched for very low mass stellar and substellar (extra-solar giant planet and brown dwarf) companions to young main sequence and late M dwarf stars. Nineteen additional stars, similarly observed in our circumstellar disk program, were also examined for evidence of companions. We discuss the large depth and dynamic range of these surveys which have given rise to several putative and confirmed detections. Using follow-up spectrographic observations obtained with the Space Telescope Imaging Spectrograph (STIS) we have begun to characterize the physical nature of the objects found in the companion search program.

1. Introduction

Is there a continuity of companion objects across the sub-stellar mass-spectrum bridging the stellar main sequence into the planetary domain? If so, in what sort of local environments will these objects form? At what distances will they be found from their primaries and how might this be affected by the characteristics of the primary and companion objects and of the circumstellar regions? What implications will the discovery and characterization of such objects have for our understanding of the formation mechanisms of extra-solar planetary systems?

To begin answering these fundamental questions we have searched for candidate brown dwarf and extra-solar giant planet (EGP) companions and circumstellar debris disks in a direct imaging survey using the HST/NICMOS coronagraph. Our survey of 84 stars is sensitive to transitional and substellar companions over a broad range of masses and separations. Our disk imaging program is discussed elsewhere in these conference proceedings (Weinberger et al. 2000); here we concentrate on our companion survey. With the NICMOS coronagraph, and exploiting the highly stable characteristics of the HST+NICMOS point spread function (PSF) on sub-orbit timescales, we are able to image unresolved objects 13 to 15 magnitudes fainter than the occulted stars at distances of only a few arc seconds (Schneider 1998), thus identifying companion candidates for follow-up observations. To unequivocally establish the physical association of a companion candidate with its suspected primary, common proper motions must be demonstrated through astrometric measurements. Spectroscopy of a putative companion is necessary to ascertain its physical nature.

2. The NICMOS Coronagraphic Survey

The first phase of this program, designed to identify candidate companion objects, was carried out as a single color survey using the F160W filter (a very close analog to H-band) where the instrumental performance for low-mass point-source detection is optimized (Lowrance et al 1998). Each star was imaged coronagraphically at two field orientations (spacecraft roll angles) in the same orbit. The coronagraph reduces the background scattered light from the primary target by factors of several to more than an order of magnitude, varying with radial distance. The PSF of the primary and residual scattered light artifacts remain fixed as the detector corotates with the spacecraft. Subtraction of the two differentially rolled frames further reduces the background light by factors of several hundred in a spatially dependent fashion. This leaves "conjugate" (positive and negative) images of any astronomical sources rolled about the target axis which may be later recombined. By combining all frames in the one orbit per target allocated for the NICMOS coronagraphic survey, companion objects as faint as H $\sim$ 23 can be detected a few arc seconds from many of our primary targets (Schneider et al 1998). For the youngest stars in our census, evolutionary (cooling) models by Burrows et al (1997) and others indicate that this sensitivity limit corresponds to companion masses extending into the Jovian domain. This differential imaging strategy was generally adopted in our coordinated observing programs under the umbrella of the NICMOS IDT's Environments of Nearby Stars investigations. While different in detail, those programs may be be summarized as follows:

A Search For Massive Jupiters. Thirty-eight very young main-sequence stars with a mean distance of $\sim$ 30pc were observed. The median age for the selected targets with well-established ages is $\sim$ 90 Myrs, with eight targets as young as $\leq$ 10 Myrs. Substellar companions to young stars are still in early cooling phases and are more readily detectable as a result of their elevated luminosities (L $\sim$ $t^{-1.3}$ $M^{2.24}$). Among the youngest targets are several members of the TW Hydra Association (TWA), a loose stellar association of (perhaps) two dozen identified members (Webb & Zuckerman 1999), all $\sim$ 10 Myrs of age, comprising the nearest site of recent star formation to the Earth (d $\sim$ 50pc).

A Search for Low Mass Companions to Nearby M Stars. Twenty-seven M-dwarfs which are a) very nearby (d $\leq$ 6pc) with spectral types later than M3.5; b) young (age $\leq$ 10 My) with d $\leq$ 25pc; and c) spectrally the latest known (i.e, "ultra-cool" dwarfs later than $\sim$ M8.5) were observed. For the nearest stars in this sample, the minimum separations for companion detections are as small as 1.2 AU.

Dust Disks around Main Sequence Stars. Stars with large IRAS excesses and other indicators of the likely presence of circumstellar dust were observed at 1.1 and/or 1.6 microns. Shorter wavelength observations provide better coronagraphic sensitivity for circumstellar scattered light which will closely follow the spectral energy distributions of the central stars. While observations were tailored for disk detection, all images were analyzed for the possible presence of close low-mass companions.

In a limited number of cases, we obtained follow-up observations of newly-found candidates in other NICMOS filters before the cryogenic coolant in NICMOS was exhausted. The color information was used to discriminate ill-placed unresolved background objects from likely physical companions.

3. Extra-Solar Giant Planet Detection

NICMOS coronagraphy enables the direct imaging of young EGPs. This is demonstrated in the case of a candidate EGP companion to TWA6 (ROSAT116, H=6.9, K7V). This X-ray source is a TWA member and has an estimated age of $\sim$ 10 Myr, concurrent with the ensemble age of other association members. As shown in Figure 1 (left), the H=20.1 putative companion is seen with a S/N of 50 at an angular separation of $2\farcs5$ (125 AU projected distance) from its primary which is brighter by 13.2 magnitudes. In a follow-up NICMOS camera 1 observation at 0.9μm (F090M filter) the object was unseen to a (less-sensitive) 3σ 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 TWA6, its absolute H magnitude suggests an effective surface temperature of $\sim$ 800K (for an surface gravity of 7.5x10^4) and a mass of $\sim$ 1 Jupiter based upon evolutionary models by Burrows et al (1997).

In the case of TWA6“B”, as well as a number of other substellar companion candidates, we are obtaining HST/STIS 0.75-1.0 μm spectra of the objects to help elucidate their physical natures. We are also attempting to measure differential proper motions to establish (or reject) physical association with ground-based adaptive optics facilities. Such astrometric measures may be difficult with the current temporal baseline of less than two years. Re-observations with NICMOS, when it is returned to service in HST Cycle 10, should unequivocally establish whether or not TWA “A” and“B” are gravitationally bound, and hence if TWA6“B” is a young Jovian planet.

While the unambiguous determination of the planetary nature of a suspected companion demands dynamical and spectroscopic confirmation, the rejection of putative young EGJs may be done with high confidence based on their color indices. For example, a more luminous candidate companion object with an apparent H magnitude of 16.8 was identified at a similar distance from another TW Hydra association member, TWA7 (M1V, H=7.4) as shown in Figure 1 (right). A later NICMOS observations found its I'[F090M(0.9μm)] - H color to be +0.88, too blue to be a substellar object at the age of the primary, and most-likely a background K star. One might conjecture extrinsic temporal variations in the color indices arising, for example, from cometary impacts. This

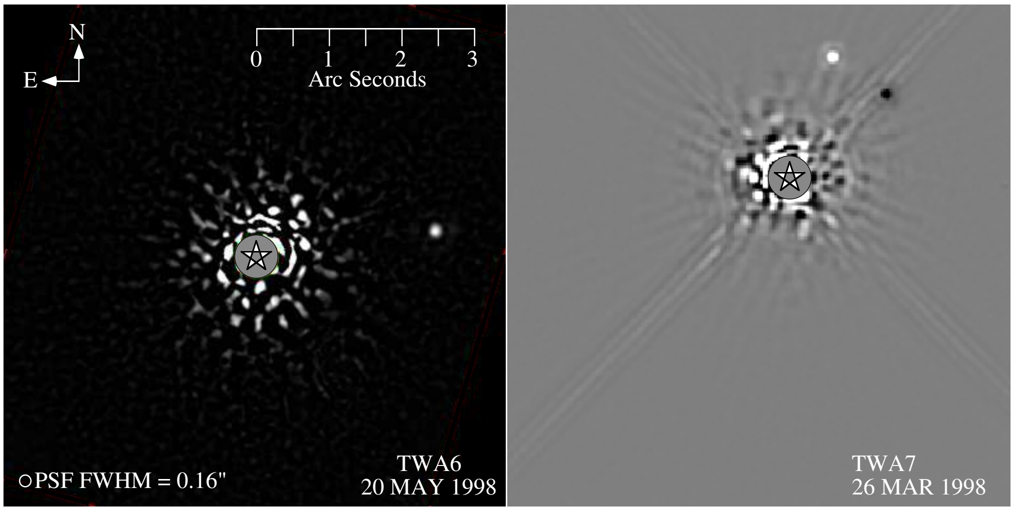

Figure 1. NICMOS F160W coronagraphic images of TW Hydra association members TWA6 (left, reconstructed from rotated difference image conjugates), and TWA7 (right, difference image).

is an unlikely scenario as a sustained blueing of more than an order of magnitude would be required for a 10 Myr EGP of this H-band luminosity to mimic a background star of the same color.

4. Brown Dwarfs

Recently, many old 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 were subsequently confirmed spectroscopically. Indeed, it has been suggested that brown dwarfs, once considered somewhat exotic objects, may be as common as stars. Yet, the companion mass fraction of these substellar objects, which occupy a niche in the mass function between planets and stars, remains largely unknown. How common are they? Do companion brown dwarfs form in a process more like planets than stars? How does the presence of a brown dwarf companion effect the evolution of a newly-forming solar system? Our small NICMOS survey begins to address these questions but many more objects will have to be studied before they are fully answered.

The first brown dwarf companion candidate identified from the NICMOS surveys, TWA5B (CD -33°7796B, M1.5V, H=7.2) as reported by Lowrance et al (1999), is also a member of the TW Hydra association. The H=12.14 magnitude (Vega system) companion is readily seen in the NICMOS coronagraphic difference image shown in Figure 2 (left) with a separation of 1$''\!.$96 (98 AU projected distance) at a PA of 358$^\circ\!.$9. Direct imaging with the KeckI/NIRC and KeckII/LRIS acquisition cameras (possible given the modest primary/secondary contrast ratio and sufficiently large separation) show color indices of I-J = 3.2, I-H=3.7, and I-K = 4.4. With an absolute H magnitude of 8.41 (assuming physical association, so d = 50 pc) and a bolometric correction of BC(H) = 2.8

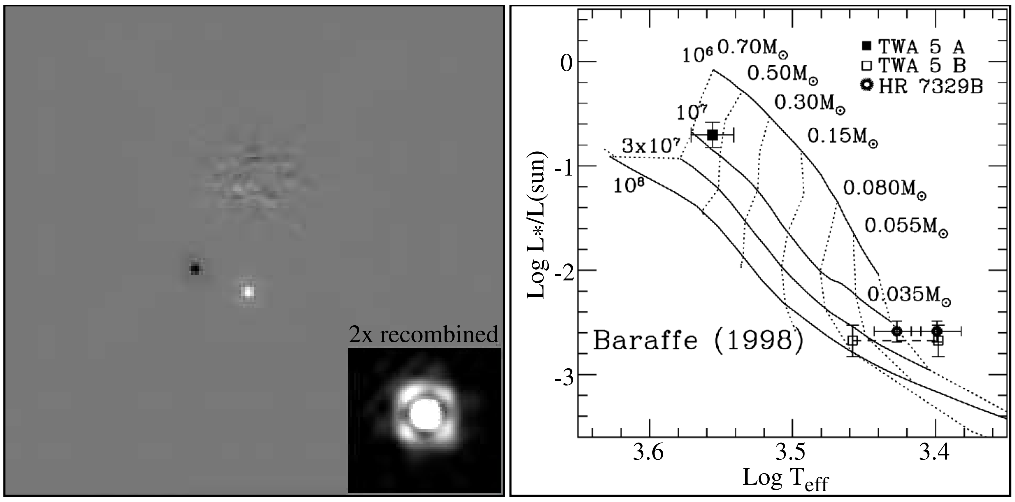

Figure 2. (Left) F160W coronagraphic difference image of TWA5B (recombined image inset). (Right) Placement of TWA5A/B & HR7329B on evolutionary tracks.

we ascertained its luminosity as 0.0021 $L_\odot$ and its effective temperature as $\sim$ 2600K.

Young, and therefore hot, brown dwarfs have spectra resembling M dwarf stars of the same photospheric temperatures. Thus we photometrically classify TWA5B as M8.5V. Using evolutionary tracks from Baraffe (1998) (see Figure 2, right) and others we estimate the mass of the object to be $\sim$ 0.02 $M_\odot$ (20 Jupiters). We recently obtained a short-wavelength NIR spectrum using the G750M grating in STIS. We compare the 8000-9000Å spectrum of TWA5B to that of two late M-dwarf standards, J2309+1594 (M8.5V) and J1239+2029 (M9V), (see Figure 3) for which we find a very good fit confirming our photometrically determined photospheric temperature and spectral classification.

We compare TWA5B with a second brown dwarf companion identified with NICMOS and confirmed spectroscopically with STIS, HR 7329B (Lowrance, et al 2000). The older ($\sim$30 Myr) A0V star (H=5.05) is at a comparable distance of 47pc. Assuming companionship for the $4\farcs17$ distant unresolved object (196 AU projected distance), the H=11.90 companion candidate imaged by NICMOS at a PA of $166\fdg8$ was estimated to have a luminosity of 0.0026 $L_\odot$ (Habs = 8.54 with BC(H)=2.67). As with CD -33°7795 we place HR 7329B on evolutionary models and find a mass of $\sim$ 0.04$M_\odot$ (40 Jupiters). Its spectrum, from which we deduce a spectral class of M7.5V, is shown in Figure 3 along with TWA5B and the M7V and M8V spectral standards VB8 and VB10, respectively.

In conclusion, we look forward to the return of NICMOS in HST cycle 10 which will permit an expansion of this stellar survey, and unambiguous astrometric follow-up of our already identified companion candidates.

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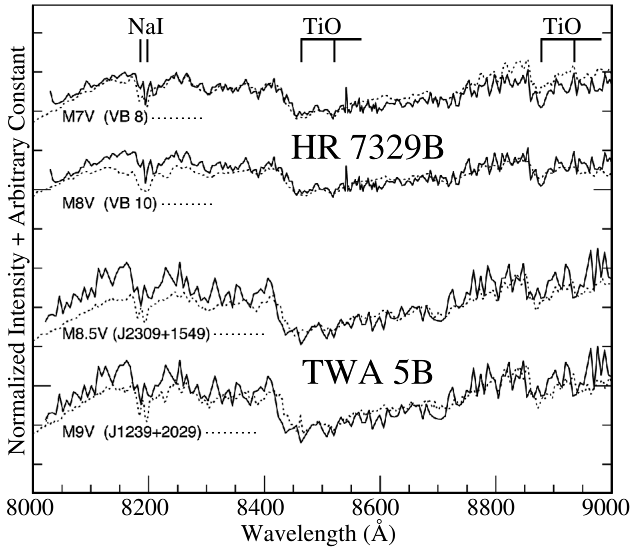

Figure 3. STIS spectra of TWA5B, HR7329B, and late M-dwarfs

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