

A CANDIDATE SUBSTELLAR COMPANION TO CD $-33^{\circ}7795$ (TWA 5)

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ABSTRACT

We present the discovery of a candidate substellar object in a survey of young stars in the solar vicinity using the sensitivity and spatial resolution afforded by the NICMOS coronagraph on the *Hubble Space Telescope*. The $H = 12.1$ mag object was discovered approximately $2''$ from the TW Hydrae association member CD $-33^{\circ}7795$ (TWA 5), and the photometry implies a spectral type M8–M8.5, with a temperature of ~ 2600 K. We estimate that the probability of a chance alignment with a background object of this nature is less than 2×10^{-5} and therefore postulate that the object (TWA 5B) is physically associated at a projected separation of 100 AU. Given the likely youth of the primary (~ 10 Myr), current brown dwarf cooling models predict a mass of $\approx 20M_{\text{Jup}}$ for TWA 5B.

Subject heading: stars: low-mass, brown dwarfs

1. INTRODUCTION

The discovery and study of low-mass objects in stellar systems is one of the key goals of contemporary observational astronomy. The substellar mass range from 10 to $80M_{\text{Jup}}$ (0.01 – $0.08 M_{\odot}$), of which no objects were known 10 years ago, is crucial to our understanding of both stellar and planetary formation. Today, a handful of such objects are known. To make further progress, we are conducting an imaging survey of young, main-sequence stars to search for substellar companions using infrared coronagraphic techniques. Substellar objects cool with age because they do not sustain hydrogen fusion and become more difficult to detect with time as they become both fainter and redder (see Burrows et al. 1997). Using independently determined ages and distances for the target stars, the masses of detected secondaries can be ascertained from infrared magnitudes and theoretical evolutionary tracks on the H-R diagram.

Over the last few years, mounting evidence has suggested that a number of young, active stars in the vicinity of TW Hydrae form a physical association with an age of ~ 10 Myr (Kastner et al. 1997; Webb et al. 1998b; Soderblom et al. 1998). At an approximate distance of 50 pc, the “TW Hydrae association” (TWA) is the region of recent star formation nearest to the Sun (Kastner et al. 1997). Recently, Webb et al. (1998b) added HR 4796 and identified five new systems (seven members), in which each system is characterized by the presence of X-ray emission, $H\alpha$ emission, and strong lithium absorption associated with young stars. The currently identified 11 systems are shown to have similar space motions implying physical association and a possible common origin (Webb et al. 1998a). Webb et al. (1998a) identify CD $-33^{\circ}7795$, a member of this association, as a likely spectroscopic binary, and although chromospheric activity can be enhanced in short-period, tidally locked binaries (Barrado Y Navascues & Stauffer 1996), they argue it is a member due to the presence of a strong Li line

and consistent space motion with other TWA members. In their listing of the members of the TW Hya association, Webb et al. (1998b) use the provisional designation TWA 5 for CD $-33^{\circ}7795$, which we also adopt.

In this Letter we present observations of TWA 5B, the first substellar object discovered with the coronagraph on the Near-Infrared Camera and Multi-Object Spectrometer (NICMOS) aboard the *Hubble Space Telescope* (*HST*). We discuss observation and reduction techniques which may prove important to other coronagraphic programs. We then present the measured and inferred properties from *HST*/NICMOS and Keck/Low-Resolution Imaging Spectrometer (LRIS) and Near-Infrared Camera (NIRC) observations of the newly discovered companion. TWA 5B was discovered independently at the Infrared Telescope Facility using speckle imaging as reported in a companion Letter by Webb et al. (1998b).

2. OBSERVATIONS

2.1. NICMOS

TWA 5 (CD $-33^{\circ}7795$; R.A. = $11^{\text{h}}31^{\text{m}}55^{\text{s}}.3$, decl. = $-34^{\circ}36'27''$ (J2000.0; M1.5 V) was observed with NICMOS on 1998 April 25, 07:43–08:40 UT. We imaged the star using the coronagraph in Camera 2 (pixel scale $\approx 0''.076$ pixel $^{-1}$) in combination with a wide-band F160W filter (central wavelength: $1.59 \mu\text{m}$, $\Delta\lambda = 0.40 \mu\text{m}$), which corresponds closely to a Johnson H -band photometric filter. We obtained two multiple-exposure images with the bright primary star TWA 5 behind the coronagraph (radius = $0''.3$) at two orientations differing by $29^{\circ}9$. While the stellar point-spread function (PSF), the instrumental scattering function, and detector artifacts rotate with the aperture, any real features in the unocculted area of the detector will be unaffected by a change in the camera orientation. Subtraction of these two images has been shown to further reduce residual PSF background light (Schneider et al. 1998). Three standard NICMOS STEP64 MultiAccum (non-destructive read) integrations (MacKenty et al. 1997) totaling 684 s were executed at each orientation.

The NICMOS coronagraphic images were reduced and processed utilizing calibration darks and flat fields created by the NICMOS Instrument Design Team (IDT) from on-orbit observations. The raw image data were calibrated in an analog

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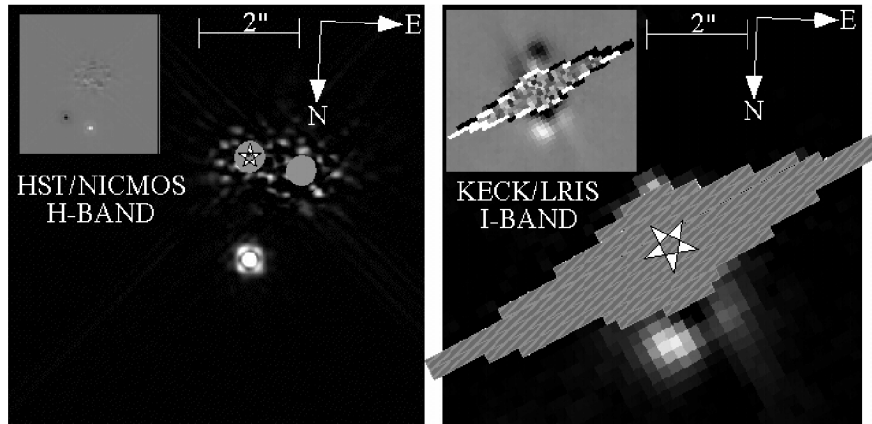


FIG. 1.—*Left*: NICMOS *H*-band image of TWA 5B. Observations at two different orientations have been subtracted with TWA 5A behind the coronagraph. The inset shows positive and negative images of TWA 5B rotated $29^{\circ}9$ about the primary's center. Combining the two conjugate images of the secondary by image translation, the diffraction-limited profile of the companion is seen. The residual light not rejected by the coronagraph appears in two positions from the translation centered on the hole locations. Pixels inside the hole have been set to gray. The orientation of the image corresponds to the primary on the left, marked with a star. *Right*: LRIS image of TWA 5A which has been rotated by 180° and subtracted from itself. The companion is seen to the north and its conjugate negative to the south (*inset*). There is residual light from incomplete subtraction of the diffraction spikes to the east of the secondary. The primary is saturated (see inset); the saturated pixels have been set to gray.

to the pipeline reduction software CALNICA (Bushouse 1997), which performs a dark subtraction, fits the multiaccum data using linear regression, and flat-fields the images. No explicit background correction was made at this step because the differencing of the two coronagraphic images removed scattered light and any background light. Two additional steps were performed before flat-fielding: one that used the first reads in the multiaccum sets to estimate the signals in pixels which saturated in later reads, and another that removed an estimate of the residual DC offsets left after subtracting the dark current. Following initial calibration, bad pixel values were replaced by a weighted interpolation with a radius of 5 pixels. The three multiaccums at each orientation were then averaged to create final calibrated images. The images from each of the two spacecraft orientations were then aligned and subtracted from each other, leaving lower amplitude residual noise near the coronagraphic hole edge as well as positive and negative conjugates of any objects in the field of view. The raw data were reduced independently in a similar manner using the NICRED program (McLeod 1997).

2.2. Keck

We obtained an *I*-band ($\lambda = 0.73\text{--}0.92 \mu\text{m}$) image of TWA 5 on 1998 February 6 UT on the Keck II 10 m telescope using the LRIS (Oke et al. 1995) in imaging mode. A short (1 s), direct image was taken, but even in this minimal integration time, the primary star saturated, causing some bleeding. Under the assumption that the LRIS PSF is azimuthally symmetric, the image was rotated by 180° and subtracted from itself to search for possible bright, close secondaries.

TWA 5 was observed on 1997 January 18 UT using the NIRC (Matthews & Soifer 1994) on the Keck I 10 m telescope. Two short exposure (0.43 s), direct images using both *J* ($\lambda = 1.1\text{--}1.4 \mu\text{m}$) and *K* ($\lambda = 2.0\text{--}2.4 \mu\text{m}$) filters were taken, bias subtracted, and flat-field corrected. Sky subtraction was accomplished via the standard technique of dithering a few arcseconds and differencing the two frames.

3. RESULTS

Subtraction and analysis of the NICMOS coronagraphic images reveal a stellar-like object (TWA 5B) at a separation of $1''.96 \pm 0''.01$ and a position angle of $179^{\circ} \pm 0''.36$ from TWA 5 (TWA 5A) (Fig. 1, *left*). This secondary is pointlike with an FWHM of $0''.14$ derived from the coronagraphic images, similar to the primary's FWHM of $0''.15$ derived from the acquisition images. The secondary is also seen in the LRIS (Fig. 1, *right*) and NIRC (not shown) direct images at the same position angle and separation. The positions of the primary and secondary in the NICMOS images were found by a least-squares isophotal ellipse fitting process around the PSF core with a radius of 7 pixels to exclude flux from any close objects. Since the target star is occulted in the NICMOS coronagraphic images, its position is ascertained from the target acquisition image, which resulted in independent measurements of each offset and position from both orientations.

3.1. NICMOS

In order to measure the flux of the secondary in the NICMOS images, the image conjugates (positive and negative) were separated after subtraction, then shifted (translated, not rotated) with bicubic interpolation/resampling to null-out/align the PSF of the companion. The positive and negative images were combined to produce a reconstructed image of the companion with the background suppressed except for residual photon noise (Fig. 1, *left*).

The magnitude of TWA 5B was measured using a 15×15 pixel square aperture centered on the companion. A correction factor of 14%, determined from coronagraphic photometric curves of growth developed by the NICMOS IDT, was applied to the measured flux to compensate for the flux that fell out of this aperture. With a conversion factor for the F160W filter of $2.20 \times 10^{-6} \text{ Jy ADU}^{-1} \text{ s}^{-1}$ and 1087 Jy corresponding to an *H* magnitude of zero (M. Rieke 1998, private communication), the *H* magnitude of TWA 5B is 12.13 ± 0.05 mag. The photometry of the NICRED reduced images is consistent with these results with a measured *H* magnitude of $12.16 \pm$

TABLE 1
MEASURED PHOTOMETRY OF TWA 5A AND B

Source	Spectral Type	I	J	H	K
5A	M1.5	8.8 ± 0.4^a	7.7 ± 0.1^a	7.2 ± 0.1	6.8 ± 0.1^a
5B	~M8.5	15.8 ± 0.2	12.6 ± 0.2	12.14 ± 0.06	11.4 ± 0.2

^a From Webb et al. (1998b).

0.06 mag for TWA 5B. The uncertainty is dominated by NICMOS's calibration in relation to standard stars. For the remainder of the Letter, we will use an H magnitude of 12.14 ± 0.06 for TWA 5B (Table 1).

The H -band magnitude of TWA 5A was determined from aperture photometry of the two calibrated target acquisition images (at each of the two spacecraft orientations) processed as described in § 2.1. Both measurements overlapped within the uncertainties and were averaged to yield $H = 7.2 \pm 0.1$ mag (Table 1).

3.2. Keck

The I -band flux of TWA 5B was measured from the one, direct LRIS image. In the rotated and subtracted image (Fig. 1, right), a circular aperture with a radius of 3 pixels ($0''.45$) was used to minimize the influence of spillover light from the primary. The flux measured in the aperture was corrected relative to an 8 pixel ($1''.2$) radius aperture using bright objects in the LRIS field of view. Comparing the measured signal with a white dwarf, HZ4, for which $I = 14.7$ mag (Zuckerman & Becklin 1987), we find $I = 15.8 \pm 0.2$ mag for TWA 5B. The majority of the uncertainty in the measure lies in the aperture correction due to the proximity of the saturated primary.

As in the LRIS images, the primary is also saturated in the NIRC direct images, but circular aperture photometry was performed on the secondary using small apertures to decrease the influence of light from the primary. The measured J and K magnitudes of TWA 5B (Table 1) harbor systematic uncertainties resulting from poorly calibrated curves of growth of both the object and standard stars. We estimate these uncertainties to be ≈ 0.2 mag.

4. DISCUSSION

4.1. Likelihood of Companionship

With our data set it is not possible to prove a physical association of TWA 5A and TWA 5B. However, we can compare the apparent brightness ($J = 12.6$ mag) and red color ($I - K = 4.4$) with objects found in various other infrared surveys. From the J. D. Kirkpatrick, T. Henry, & D. W. McCarthy (1998, private communication) survey of the solar neighborhood, we find ≈ 0.2 stars arcmin^{-2} at $J < 13$ mag at the Galactic latitude of TWA 5A ($b = 25^\circ$) (we extrapolate from their completeness limit of $J < 17$ mag using Lilly & Cowie's [1987] Galactic distribution model). Hence, the a priori probability of finding an object of this brightness within a $2''$ radius circle (area = 0.0035 arcmin^2) of any given point is about 0.06%. In an infrared survey of the Pleiades, Simons & Becklin (1992) found colors for ≈ 500 background objects in 275 deg^2 ; only 3% had $I - K > 3.5$ mag. Most of those red objects were likely background galaxies which would be resolved by *HST*. Therefore, we estimate the probability that a red background star is separated from TWA 5A by $2''$ is the product of these two, or less than 2×10^{-5} .

We consider the possibility that TWA 5B could be a fore-

ground, low-mass star. Assuming a spectral type later than M7 from the colors, we find $M_H > 10.15$ for a dwarf star (Kirkpatrick & McCarthy 1994), so the photometric distance would be 25 pc. Henry (1991), in a volume-limited infrared survey, finds six objects with $M_H > 9.5$ within 5 pc from the Sun. Assuming a spherical distribution of low-mass stars in the solar neighborhood, we should expect 750 such objects out to 25 pc, so the a priori probability of finding one in projection within a $2''$ radius circle is 2×10^{-8} .

Given these small probabilities, it is unlikely that we would find a foreground or background object of this nature in our sample size of less than 50 stars. The combination of a small separation from another low-mass star, an extremely red color, and moderate brightness is rare at a Galactic latitude of 25° . Further, as shown below, TWA 5B falls on the same isochrone as TWA 5A on the H-R diagram, implying coevality and therefore companionship. For the remainder of the Letter, we assume that TWA 5B is physically associated with TWA 5A.

4.2. Effective Temperature and Bolometric Luminosity

The photometric measurements place strong constraints on the nature of the secondary. The colors of TWA 5B are consistent with a spectral type of M8–M8.5 (Kirkpatrick & McCarthy 1994; Luhman, Leibert, & Rieke 1997). An effective temperature is required to position TWA 5B on an H-R diagram, but the temperature scale for late, young M dwarfs is uncertain (Allard et al. 1997). Kirkpatrick et al. (1993) match synthetic spectral fits to observed spectra for late-type stars and derive temperatures of 2875 and 2625 K for M8 and M9, respectively. Luhman & Rieke (1998) extrapolate from Leggett et al.'s (1996) model fits to derive 2505 K for this spectral class, which agrees with the newer models used by Leggett, Allard, & Hauschildt (1998). Simons et al. (1996) present a derived relation between color and effective temperature, which gives 2538 K for the $J - K$ color we measure. Since many young, low-mass stars possess spectral features indicative of both dwarfs and giants (Luhman & Rieke 1998), it has been argued that adopting an intermediate effective temperature for the two luminosity classes, 100–150 K hotter than the dwarf scale, is appropriate (Luhman et al. 1997; White et al. 1998). Perrin et al. (1998) have found an M8 giant to have an effective temperature of 2806 K from their model fits. With the uncertainty in temperature for late M dwarf stars and the added uncertainty from the youth, we plot the range (Fig. 2) appropriate to the colors we measure with a horizontal dotted line from 2505 to 2875 K, which includes the derived giant temperature. Assuming coevality with TWA 5A, the primary's isochrone intersects this range at approximately 2600 K.

There is no parallax distance measured to TWA 5, so we adopt the approximate distance of 50 pc to the association. This is based on *Hipparcos* parallax measures to TW Hydra, HD 98800, HR 4796, and TWA 9, which are thought to be members of the same association. With an H magnitude of 12.14 and a distance modulus of 3.49, we derive the luminosity of TWA 5B to be $0.0021 \pm 0.0003 L_\odot$. In doing so, we adopt

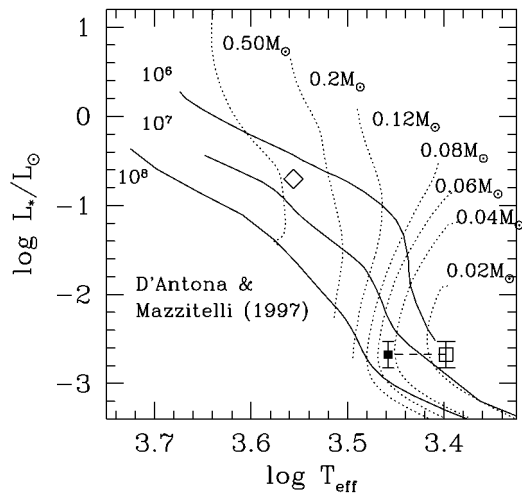


FIG. 2.—Evolutionary tracks (D’Antona & Mazzitelli 1997) with TWA 5A (open diamond) and TWA 5B (squares) plotted. The dashed horizontal line represents an uncertainty in assigning a photometric temperature to a young star (see text for discussion). The assumption of coevality between TWA 5A and TWA 5B would have an isochrone intersect at a temperature ≈ 2600 K and at a mass of $20M_{\text{Jup}}$.

a bolometric correction of 2.8 ± 0.1 mag for an M8.5 dwarf, as suggested by Kirkpatrick et al. (1993).

4.3. Derived Mass

We place TWA 5A and B on pre-main-sequence evolutionary tracks (D’Antona & Mazzitelli 1997) to infer masses (Fig. 2). The range of temperatures plotted places the mass of the secondary in the range of $0.015\text{--}0.055 M_{\odot}$ ($15\text{--}55M_{\text{Jup}}$) with the primary’s isochrone, assuming coevality, intersecting at $\approx 20M_{\text{Jup}}$. Evolutionary tracks themselves do differ somewhat due to different models and atmospheres used. The tracks of (Baraffe et al. 1998) place the mass of the secondary in the range $15\text{--}60M_{\text{Jup}}$, with the primary’s isochrone intersecting near

$25M_{\text{Jup}}$. Burrows et al.’s (1997) models predict a 10 Myr old, $20M_{\text{Jup}}$ brown dwarf will have an effective temperature of 2609 K and a luminosity of $0.0022 L_{\odot}$, which is in good agreement with our data.

5. IMPLICATIONS FOR FORMATION OF BROWN DWARF COMPANIONS

We present spatially resolved, high signal-to-noise ratio optical and near-infrared photometry of the young (~ 10 Myr) TW Hydrae association member CD $-33^{\circ}7795$ (=TWA 5) with evidence for an approximately $20M_{\text{Jup}}$ brown dwarf companion at a projected separation of 100 AU from the primary. If indeed the secondary is a true companion, it will be interesting to see if a young brown dwarf exhibits Li absorption as do all known members of the TWA (Webb et al. 1998b). It has been conjectured that brown dwarfs with mass $10\text{--}80M_{\text{Jup}}$ are rare at separations less than 5 AU (Marcy et al. 1998) and greater than 200 AU (Oppenheimer, Kulkarni, & Stauffer 1998), but there are now at least four likely substellar companions known at separations from 30 to 200 AU (Kirkpatrick et al. 1998; Nakajima et al. 1995; White et al. 1998; this work). Although orbiting diverse primaries (white dwarf, field M star, T Tauri star, young M star) and subject to small number statistics, these results hint that the semimajor axis distribution of brown dwarf and late M dwarf secondaries may differ since the latter are found throughout a wide range of semimajor axes.

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REFERENCES

- Allard, F., Hauschildt, P. H., Alexander, D. R., & Starrfield, S. 1997, *ARA&A*, 35, 137
- Baraffe, I., Chabrier, G., Allard, F., & Hauschildt, P. H. 1998, *A&A*, 337, 403
- Barrado Y Navascues, D., & Stauffer, J. R. 1996, *A&A*, 310, 879
- Burrows, A., et al. 1997, *ApJ*, 491, 856
- Bushouse, H. 1997, in *HST Calibration Workshop*, ed. S. Casertano & C. Skinner (Baltimore: STScI), 223
- D’Antona, F., & Mazzitelli, I. 1997, *Mem. Soc. Astron. Italiana*, 68, 4
- Henry, T. 1991, Ph.D. thesis, Univ. Arizona
- Kastner, J. H., Zuckerman, B., Weintraub, D. A., & Forveille, T. 1997, *Science*, 277, 67
- Kirkpatrick, J. D., Allard, F., Bida, T., Becklin, E. E., Zuckerman, B., Chabrier, G., & Baraffe, I. 1998, *ApJ*, in press
- Kirkpatrick, J. D., Kelley, D. M., Rieke, G. H., Liebert, J., Allard, F., & Wehrse, R. 1993, *ApJ*, 402, 643
- Kirkpatrick, J. D., & McCarthy, D. W. 1994, *AJ*, 107, 333
- Leggett, S. K., Allard, F., & Hauschildt, P. H. 1998, *ApJ*, 509, 836
- Leggett, S. K., Allard, F., Berriman, G., Dahn, C. C., & Hauschildt, P. H. 1996, *ApJS*, 104, 117
- Lilly, S. J., & Cowie, L. L. 1987, in *Infrared Astronomy with Arrays*, ed. C. G. Wynn-Williams, E. E. Becklin, & L. E. Good (Honolulu: Institute for Astronomy), 473
- Luhman, K. L., Leibert, J., & Rieke, G. H. 1997, *ApJ*, 489, L165
- Luhman, K. L., & Rieke, G. H. 1998, *ApJ*, 497, 354
- Marcy, G. W., Butler, R. P., Vogt, S. S., Fischer, D., & Lissauer, J. J. 1998, *ApJ*, 505, L147
- Matthews, K., & Soifer, B. T. 1994, in *Infrared Astronomy with Arrays: the Next Generation*, ed. I. McLean (Dordrecht: Kluwer), 239
- MacKenty, J. W., et al. 1997, *NICMOS Instrument Handbook*, Version 2.0 (Baltimore: STScI)
- McLeod, B. 1997, in *1997 HST Calibration Workshop*, ed. S. Casertano & C. Skinner (Baltimore: STScI), 281
- Nakajima, T., Oppenheimer, B. R., Kulkarni, S. R., Golimowski, D. A., Matthews, K., & Durrance, S. T. 1995, *Nature*, 378, 463
- Oke, J. B., et al. 1995, *PASP*, 107, 375
- Oppenheimer, B. R., Kulkarni, S. R., & Stauffer, J. R. 1998, in *Protostars and Planets IV*, ed. V. Mannings, A. Boss, & S. Russell (Tucson: Univ. Arizona Press), in press
- Perrin, G., Forrester, V. C., Ridgway, S. T., Mariotti, J.-M., Traub, W. A., Carleton, N. P., & Lacasse, M. G. 1998, *A&A*, 331, 619
- Schneider, G., Thompson, R. I., Smith, B. A., & Terrell, R. J. 1998, *Proc. SPIE*, 3356, 222
- Simons, D. A., & Becklin, E. E. 1992, *ApJ*, 390, 431
- Simons, D. A., Henry, T. J., & Kirkpatrick, J. D. 1996, *AJ*, 112, 2238
- Soderblom, D. R., et al. 1998, *ApJ*, 498, 385
- Webb, R. A., Reid, I. N., & Zuckerman, B. 1998a, in preparation
- Webb, R. A., Zuckerman, B., Patience, J., White, R. J., Patience, J., Schwartz, M., McCarthy, C., & Platais, I. 1998b, *ApJ*, in press
- White, R. J., Ghez, A. M., Reid, N. I., & Schultz, G. 1998, in preparation
- Zuckerman, B., & Becklin, E. E. 1987, *ApJ*, 319, L99