THE GEMINI NICI PLANET-FINDING CAMPAIGN: DISCOVERY OF A CLOSE SUBSTELLAR COMPANION TO THE YOUNG DEBRIS DISK STAR PZ Tel*

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ABSTRACT

We report the discovery of a tight substellar companion to the young solar analog PZ Tel, a member of the β Pic moving group observed with high-contrast adaptive optics imaging as part of the Gemini Near-Infrared Coronagraphic Imager Planet-Finding Campaign. The companion was detected at a projected separation of 16.4 ± 1.0 AU (0.33 ± 0.01) in 2009 April. Second-epoch observations in 2010 May demonstrate that the companion is physically associated and shows significant orbital motion. Monte Carlo modeling constrains the orbit of PZ Tel B to eccentricities >0.6. The near-IR colors of PZ Tel B indicate a spectral type of M7 ± 2 and thus this object will be a new benchmark companion for studies of ultracool, low-gravity photospheres. Adopting an age of 12.8 ± 6 Myr for the system, we estimate a mass of 36 ± 6 MJup based on the Lyon/DUSTY evolutionary models. PZ Tel B is one of the few young substellar companions directly imaged at orbital separations similar to those of giant planets in our own solar system. Additionally, the primary star PZ Tel A shows a 70 μm emission excess, evidence for a significant quantity of circumstellar dust that has not been disrupted by the orbital motion of the companion.

Key words: brown dwarfs instrumentation: adaptive optics planetary systems planets and satellites: detection stars: pre-main sequence

Online-only material: color figures

1. INTRODUCTION

High-contrast imaging has recently yielded the first direct images of young extrasolar planets (Marois et al. 2008; Kalas et al. 2008; Lafrenière et al. 2008; Lagrange et al. 2009) and a number of other substellar companions (Chauvin et al. 2005; Itoh et al. 2005; Luhan et al. 2006; Schwalm et al. 2008; Thalmann et al. 2009), largely at separations >50 AU. Only a handful of substellar or planetary mass companions have been found at separations <20 AU, including the recently confirmed planet imaged around β Pic (Lagrange et al. 2010) and a few substellar companions around older (>Gyr) stars (e.g., HR 7672 B: Liu et al. 2002; SCR 1845-6357AB: Biller et al. 2006).

The Near-Infrared Coronagraphic Imager (NICI) at the 8.1 m Gemini-South Telescope (Chun et al. 2008) is a dedicated adaptive optics (AO) instrument tailored expressly for direct imaging of brown dwarf and exoplanet companions. NICI combines several techniques to attenuate starlight and suppress speckles for direct detection of faint companions to bright stars: (1) Lyot coronagraphy, (2) dual-channel imaging for Spectral Differential Imaging (SDI; Racine et al. 1999; Marois et al. 2005; Close et al. 2005; Biller et al. 2007), and (3) operation in a fixed Cassegrain rotator mode for Angular Differential Imaging (ADI; Liu 2004; Marois et al. 2006; Lafrenière et al. 2007a; Biller et al. 2008). While each of these techniques has been used individually in large planet-finding surveys (Biller et al. 2007; Lafrenière et al. 2007b; Nielsen & Close 2010), the NICI Campaign is the first time ADI and SDI have been employed simultaneously in a large survey.

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Since 2008 December, the NICI Planet-Finding Campaign (Liu et al. 2009) has been obtaining deep, high-contrast AO imaging of a carefully selected sample of ~300 young, nearby stars. We report the discovery of a close substellar companion to PZ Tel, a young solar analog (K0 spectral type) and a member of the ~12 Myr β Pic moving group (Zuckerman et al. 2001) with a Hipparcos distance of 51.5 ± 2.6 pc (van Leeuwen 2007).

2. OBSERVATIONS AND DATA REDUCTION

The NICI Campaign uses specialized observing strategies to exploit the unique capabilities of the NICI instrument. While SDI provides significant contrast gains even for non-methanated objects at separations down to 0′′7, at ~0′′3 PZ Tel B is significantly self-subtracted in our SDI data reductions. Thus, in this Letter we focus solely on ADI-based techniques. For ADI, the image rotator is turned off, and the field is allowed to rotate with the parallactic angle on the sky. The image of a true companion will rotate with the parallactic angle, while speckles will stay fixed relative to the detector. A point-spread function (PSF) for the primary star can be built and subtracted from each frame to remove the speckle pattern.

2.1. First- and Second-epoch ADI + SDI Observations

We obtained ADI and SDI observations of PZ Tel on 2009 April 11 (UT) and 2010 May 9 (UT). These observations were conducted using a flat-topped Gaussian profile focal plane mask with HWHM = 0′′32 (referred to hereafter as the 0′′32 mask), the CH4 4% Short filter (λcentral = 1.578 μm) in the blue channel, and the CH4 4% Long filter (λcentral = 1.652 μm) in the red channel. At each epoch, we acquired 45 1 minute frames in a combined ADI + SDI mode, over 16′′7 of field rotation in epoch 1 and 23′′2 in epoch 2.

Data for each camera were dark-subtracted, flat-fielded, and distortion-corrected. Sky background was negligible compared to halo brightness at the companion location and has not been removed. The focal plane mask is not completely opaque at its center, leaving an attenuated, unsaturated image of the primary star (henceforth “starspot”) which we use for image registration. Images from both channels were registered to the first blue channel image according to starspot centroid positions. To increase our sensitivity to non-methanated companions, we performed a “broadband ADI-only” reduction by combining red and blue channel images instead of subtracting them. The median combination of all the images was subtracted from each individual image to remove the light from the primary star. Individual images were then rotated and stacked.

2.2. 0′′22 Mask JHKs Observations

NICI coronagraphic observations using the narrower flat-topped Gaussian focal plane mask with HWHM = 0′′22 (hereafter 0′′22 mask) were acquired in a dual-channel mode at H and Ks bands on 2010 May 9 UT and in a single-channel mode at the J band on 2010 May 10 UT. The NICI filters are on the Mauna Kea Observatories photometric system (Simons & Tokunaga 2002; Tokunaga & Vacca 2005). We acquired 10 60 s frames in each filter with the rotator on. Frames were dark-subtracted, flat-fielded, and stacked according to the starspot centroid position. The median count level in an annulus far from the object was subtracted to remove sky background. JHKs-band images are presented in Figure 1.

The 0′′22 mask has an approximately Gaussian transmission profile, an inner flat plateau of 0′′12 radius, and an outer cutoff of 0′′4 radius. With its separation of ~0′′3, PZ Tel B is lightly attenuated by the mask. Thus, we must determine the mask transmission at both the center and at the companion’s position in order to measure the companion’s flux ratio relative to the primary. To measure the transmission as a function of radius, we acquired JHKs-band images of a Two Micron All Sky Survey (2MASS)-selected 4′ binary star. For each filter, the primary component was scanned across the mask along the same angular trajectory as PZ Tel B. Scans were begun with the primary under the starspot in order to accurately determine the mask center position. Images were taken at 0′′02 steps out to 0′′5. Integration times were chosen to keep both components unsaturated. We measured the flux ratio of the primary to the secondary as a function of the primary star displacement from the mask center using photometric apertures of 1–3 pixels in radius. For each photometry aperture, we fit a polynomial power law to the mask transmission as a function of radius assuming a perfectly transparent mask beyond 0′′43 radius. We used this fit to correct the measured flux ratio of PZ Tel B. At a separation of 0′′33, we estimate an error in our calibration of the mask transmission of 6%, 3%, and 11% in J, H, and Ks, respectively. These mask calibration errors are included in the final photometry errors.

2.3. Maskless Narrowband ADI Observations

To acquire photometry and astrometry without attenuation due to the focal plane mask, we acquired 43 maskless narrowband ADI images on 2010 May 10 UT. Each image had an
integration time of 30.4 s, and the field rotated by 25°:7 over the entire observation. The narrowband CH₄ 1% Short filter \( \lambda \text{central} = 1.587 \mu \text{m} \) was used in the red channel and the H₂ 2–1 narrowband filter \( \lambda \text{central} = 2.1239 \mu \text{m}, \text{width} \times 1.2\% \) was used in the blue channel. Data from each filter were reduced in separate ADI reductions (Section 2.3).

To correct losses due to self-subtraction from ADI (e.g., Marois et al. 2006) and to determine the photometric and astrometric uncertainties, we inserted simulated objects into each individual frame by scaling a cutout of the stellar peak and simulated \( \Delta \)mag. A JHK₅ color–color diagram for PZ Tel B compared to field objects is presented in Figure 3. While NICI photometry for PZ Tel B is reported in the MKO filter system and photometry for PZ Tel A is reported in 2MASS magnitudes, the differences between the two systems are small compared with the measurement uncertainties. PZ Tel B’s measured colors are similar to mid/late-M field dwarfs.

We estimate the mass and \( T_{\text{eff}} \) of the companion based on the DUSTY models of Chabrier et al. (2000). PZ Tel B’s \( J-H \) color is consistent with the DUSTY model colors expected from young substellar objects at 12 and 20 Myr, so use of the DUSTY models is appropriate. Age estimates for the \( \beta \) Pic moving group include 12 +8 Myr (Zuckerman et al. 2001), 13 ± 4 Myr for the \( \beta \) Pic member GJ 3305 (Feigelson et al. 2006), and 11.2 Myr (Ortega et al. 2009). To account for the age range cited in the literature, we estimated the mass using a uniform distribution of ages between 8 and 20 Myr.

We have chosen to work from the bolometric luminosity rather than absolute magnitudes; bolometric luminosities are less susceptible to uncertainties in the model atmospheres than single band magnitudes (Chabrier et al. 2000). Comparing to colors of these trends. During acceptance testing, the NICI platescale was measured at 18 mas pixel⁻¹.

For the second-epoch astrometry, we used the maskless ADI narrowband data set, measuring the centroid position of the companion relative to the unsaturated stellar peak in the final stacked image. The error was estimated from the astrometric rms scatter of the three simulated objects (Section 2.3) with \( \Delta \)mag that best matched the observed object flux. Astrometric measurements from the 0′/22 mask broadband and the 0′/3 mask ASDI data sets yielded similar results. We adopt the direct ADI results to avoid uncertainties from the mask transmission calibration.

In Figure 2, we plot the measured astrometry as well as the expected motion if PZ Tel B were a background star at infinite distance, given the first-epoch position and known proper and parallactic motion of the primary star. The motion of PZ Tel B over 13 months deviates from the background ephemeris at the 8.9σ level. Astrometry from the 0′/3 mask ASDI data sets for a fainter object \( \sim 3.8 \) away from PZ Tel is also shown in Figure 2. The relative motion for this other object changes as expected for a background object, confirming that published proper motion and parallax of the primary star combined with the astrometric calibration of NICI are accurate.

We reduced archival Very Large Telescope (VLT) NACO data of this system obtained on 2003 July 22 with the \( K_S \)–band filter and the 0′/013 pixel⁻¹ camera, originally reported in Macciò et al. (2005). If the object detected by NICI was moving with respect to PZ Tel A as a background object, it should have had a separation of \( >0.5 \) in 2003 and would have been detected at \( >15\sigma \) in the VLT data. By scaling and adding a PSF star image (from an unsaturated 2003 November NACO data set of Gl 86) to the NACO data, we estimate that PZ Tel B had a separation of \( <0.17 \) in 2003.

### 3.2. Photometry, Mass Estimates, and Limits on Other Companions in the Field

Aperture photometry was measured from both the 0′/22 mask JHK₅ data sets and the direct ADI narrowband data set using aperture sizes from 1 to 3 pixels in radius. Photometry results were consistent for all apertures; we adopt the 2 pixel aperture results (Table 1). As described in Section 2.3, simulated objects were inserted and retrieved to convert between measured flux and simulated \( \Delta \)mag and also to determine photometric errors as a function of \( \Delta \)mag. A JHK₅ color–color diagram for PZ Tel B compared to field objects is presented in Figure 3. While NICI photometry for PZ Tel B is reported in the MKO filter system and photometry for PZ Tel A is reported in 2MASS magnitudes, the differences between the two systems are small compared with the measurement uncertainties. PZ Tel B’s measured colors are similar to mid/late-M field dwarfs.

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We have chosen to work from the bolometric luminosity rather than absolute magnitudes; bolometric luminosities are less susceptible to uncertainties in the model atmospheres than single band magnitudes (Chabrier et al. 2000). Comparing to colors of Table 1

| Property                  | Primary                  | Secondary                 |
|---------------------------|--------------------------|----------------------------|
| Distance                  | 51.5 ± 2.6 pc⁴          |                            |
| Age                       | 12.8± 6 Myr⁴             |                            |
| Proper motion (μᵥ, μᵞ)    | (17.6 ± 1.1, −83.6 ± 0.8)mas yr⁻¹α |                            |
| Separation: 2009 Apr 11 UT| 0′.330 ± 0′.010 (16.4 ± 1.0 AU) |                            |
| Position angle: 2009 Apr 11 UT| 59′/0 ± 1′/0         |                            |
| Separation: 2010 May 9 UT | 0′.360 ± 0′.003 (17.9 ± 0.9 AU) |                            |
| Position angle: 2010 May 9 UT| 59′/4 ± 0′/5           |                            |
| ΔJ (mag)                  | ...                     | 5.40 ± 0.14                |
| ΔH (mag)                  | ...                     | 5.38 ± 0.09                |
| ΔK₅ (mag)                 | ...                     | 5.04 ± 0.15                |
| ACH₄ 1% short (mag)       | ...                     | 5.22 ± 0.12                |
| ΔH₂ 1–0 (mag)             | ...                     | 5.12 ± 0.13                |
| J (mag)                   | 6.86 ± 0.02e            | 12.26 ± 0.14               |
| H (mag)                   | 6.49 ± 0.05e            | 11.87 ± 0.10               |
| K₅ (mag)                  | 6.38 ± 0.02e            | 11.42 ± 0.15               |
| J – H (mag)               | 0.37 ± 0.05             | 0.39 ± 0.17                |
| H – K₅ (mag)              | 0.11 ± 0.06             | 0.45 ± 0.18                |
| M₅ (mag)                  | 3.30 ± 0.12             | 8.70 ± 0.18                |
| M₀ (mag)                  | 2.93 ± 0.12             | 8.31 ± 0.15                |
| M₀₅ (mag)                 | 2.82 ± 0.12             | 7.86 ± 0.19                |
| Spectral type             | K0                      | [M7 ± 2]d                  |
| log(L/L₀)                 | ...                     | −2.48 ± 0.07               |
| Estimated mass (from L₀)  | 1.25 ± 0.05 M₀₅e        | 36 ± 6 Mṣp                 |
| Estimated Tₑff (from L₀)  | ...                     | 2702 ± 84 K                |
| Estimated log(g) (from L₀)| ...                     | 4.20 ± 0.11 dex            |

Notes.

* van Leeuwen (2007).
  † Zuckerman et al. (2001).
  ‡ From 2MASS.
  § Estimated from JHK₅ colors (Section 3.2).
  † D’Antona & Mazzitelli (1994).
On-sky motion measured for the PZ Tel B (a) and a faint background object at 3′′8 in the same data set (b). The expected motion and 1σ uncertainty for a background object are overplotted, given the known proper and parallactic motion of the primary star, and the measured first-epoch position of the companion and background object. PZ Tel B cannot be a background object, as its motion diverges from the expected background track at the 8.9σ level. In contrast, the object at 3′′8 separation moves as expected relative to the primary for a background object. Astrometry errors are measured in separation and PA relative to PZ Tel A and converted to R.A. and decl. A 0′′.5 PA error at 3′′8 separation translates to a considerably larger linear error than the same error at 0′′.33 separation, hence the larger error bars in R.A. for the background object.

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field M dwarfs compiled by Leggett et al. (2010), we estimate SpT = M7 ± 2 for PZ Tel B. Colors vary somewhat between field M dwarfs and younger objects; thus, we have placed conservative errors on our estimated spectral type. We estimate a bolometric magnitude for PZ Tel B of 10.96 ± 0.18 mag from our measured MKs and BC = 3.1 ± 0.1 mag (using the K-band bolometric correction versus spectral-type relation from Golimowski et al. 2004a). We derive a model mass of 36 ± 6 MJup, model Teff of 2702 ± 84 K, and model log(g) of 4.20 ± 0.11 dex. Using the same input age grid and the single band magnitudes yielded similar mass estimates (see Figure 3, right panel). Using the same bolometric magnitude methodology with the grainless NextGen models from Baraffe et al. (1998), we derive similar values of 44 ± 9 MJup and 2764 ± 67 K. Interpolating over the same age range, using our derived absolute H-band magnitude and the models of Burrows et al. (1997, 2001), we also find a similar mass range of 38 ± 8 MJup.

Although a few fainter background objects were seen in the PZ Tel field at separations <8″, no other common proper motion companion was detected by NICI. We achieved 5σ contrast limits of 12.9 mag at 0″.5, 14.6 mag at 1″, and 16.6 mag at 2″/25 in our 1.6 μm SDI + ADI data set. These contrast limits were verified by extensive simulated planet tests. Interpolating from the DUSTY models of Chabrier et al. (2000) and adopting an age of 12 Myr, our observations are deep enough to detect any planets with masses ≥6 MJup at separations ≥0″.5.
3.3. Constraints on Orbital Parameters

We estimate the semimajor axis of PZ Tel B’s orbit from its observed separation. Assuming a uniform eccentricity distribution between $0 < e < 1$ and random viewing angles, Dupuy & Liu (2010) compute a median correction factor between projected separation and semimajor axis of $1.10_{-0.36}^{+0.91}$ ($68.3\%$ confidence limits). Using this, we derive a semimajor axis of $20_{-7}^{+12}$ AU for PZ Tel B based on its observed separation in 2010 May. These correspond to an orbital period estimate of $79_{-26}^{+30}$ yr for an assumed total system mass of $1.28_{-0.91}^{+4.36} M_\odot$.

We used the 2009 and 2010 NICI astrometry for PZ Tel B to place constraints on its orbital eccentricity through Monte Carlo simulations that account for astrometric errors and all possible inclinations ($0^\circ < i < 90^\circ$). For each inclination, we used $10^4$ uniformly distributed values of the PA of the ascending node ($\Omega$) to allow for different deprojections of the observed astrometry from the plane of the sky to the plane of the orbit. In $\approx30\%$ of cases, the resulting trial orbits were unbound ($r \geq 1$, $a < 0$), and these were excluded from the analysis. Most of the resulting trial orbits are highly eccentric. These results constrain the orbit of PZ Tel B to eccentricities of $>0.6$.

Figure 4. Monte Carlo constraints on inclination and eccentricity of PZ Tel B from our two epochs of NICI astrometry. For each inclination, $10^4$ values of the PA of ascending node ($\Omega$) were randomly drawn to allow for different deprojections of the observed astrometry from the plane of the sky to the plane of the orbit. In $\approx30\%$ of cases, the resulting trial orbits were unbound ($r \geq 1$, $a < 0$), and these were excluded from the analysis. Most of the resulting trial orbits are highly eccentric. These results constrain the orbit of PZ Tel B to eccentricities of $>0.6$.

(A color version of this figure is available in the online journal.)

With an estimated mass of $36 \pm 6 M_{\text{Jup}}$, PZ Tel B is among the lowest-mass companions directly imaged around a young solar analog (e.g., compilation in Zuckerman & Song 2009). There are only three other planetary or substellar companions known to date in the $\approx10$ Myr age range—the recently confirmed planet around $\beta$ Pic (Lagrange et al. 2010), the mid-to-late-L dwarf 2MASS 1207-39B in the $\approx8$ Myr TW Hydra Association (Chauvin et al. 2005), and the $\approx20 M_{\text{Jup}}$ late-M dwarf TWA 5B (Lowrance et al. 1999). PZ Tel B will be a new benchmark companion for studies of ultracool, low-gravity photospheres. The projected separation of PZ Tel B is only 18 AU, making it one of the very few substellar or planetary companions directly imaged at separations of $<20$ AU. Further astrometry and spectroscopy of this object will set additional limits on its orbital properties and provide improved estimates for effective temperature and surface gravity, better constraining the mass and formation history of this object.

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4. CONCLUSIONS

A large radial velocity given the known mass of the system that cannot be totally accounted for by projection effects. We choose not to assume an input distribution for inclination that would allow us to derive confidence limits on eccentricity, as randomly oriented orbits are not likely to be appropriate because of observational selection effects. (Highly eccentric companions are preferentially discovered face-on, which is the opposite sense of the geometrical preference for edge-on orbits, e.g., Dupuy & Liu 2010.)

The high eccentricity may be due to a dynamical interaction with another body. However, a radial velocity measurement by Soderblom et al. (1998) rules out the possibility that PZ Tel A is a double-lined spectroscopic binary. Also, PZ Tel A shows a 70 $\mu$m emission excess (Rebull et al. 2008), evidence for a significant quantity of circumstellar dust undisturbed by the orbital motion of the companion. Assuming a simple blackbody and characteristic temperature of 41 K, Rebull et al. (2008) set a minimum radius for the inner edge of 50 AU. Artymowicz & Lubow (1994) find that binaries at a range of mass ratios and disk viscosities and with eccentricities $>0.6$ will have $r_{\text{edge}} > 2.5$, where $r_{\text{edge}}$ is the inner edge of the circumbinary disk and $a$ is the semimajor axis of the binary. If the inner edge of the circumbinary disk is at 50 AU, the semimajor axis of the orbit of PZ Tel AB is likely $\approx20$ AU.

$\Omega < \Omega < 90^\circ$.)
