HD 106906 b: A PLANETARY-MASS COMPANION OUTSIDE A MASSIVE DEBRIS DISK

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1 INTRODUCTION

The handful of known planetary-mass companions at tens to hundreds of AU are already challenging planet formation theories, thus each addition to the set of directly imaged (DI) companions is valuable for understanding formation mechanisms. DI surveys are resource-intensive, as fewer than 20% of stars have giant planets at large orbital separations (e.g., Vigan et al. 2013). Therefore, there is a strong incentive to find so-called “signposts” for planets.

Systems like HR 8799 and β Pic host both planets and debris disks, with the planets likely sculpting the disks (Su et al. 2009; Lagrange et al. 2010). Several DI surveys (e.g., Apai et al. 2008) have targeted debris-hosting stars and found planet occurrence rates comparable to disk-blind surveys. However, these groups did not have or did not utilize detailed information on the debris disk morphology. We, and others (e.g., Janson et al. 2013a; Wahhaj et al. 2013), hope to improve the odds by searching for planets in systems with unusual debris disks.

We are targeting systems with infrared (IR) spectral energy distributions (SEDs) indicative of disk configurations such as two-belt (Su & Rieke 2013) and large inner cavity systems. HD 106906 falls into the second category.

HD 106906 (HIP 59960) is a member of the Lower Centaurus Crux (LCC) association, based on Hipparcos kinematics (de Zeeuw et al. 1999). The cluster has a mean age of 17 Myr, with an age-spread of ~10 Myr. HD 106906 is a negligibly reddened, pre-main-sequence F5V-type star, with an isochronal age and mass of 13 ± 2 Myr and 1.5 Mj, respectively (Pecaut et al. 2012).

In this Letter we present the first discovery of a planetary-mass companion around a debris-disk-selected star with the Magellan Adaptive Optics (MagAO) + Clio2 system. In Section 2 we describe our observations with the Clio2 and FIRE instruments. In Section 3, we confirm common proper motion using Gemini NICI and Hubble Space Telescope archival data; present near-infrared (NIR) spectroscopy of the companion to confirm its cool, young nature; estimate its mass using “hot start” evolutionary models; place limits on the presence of additional objects; and discuss the likelihood of interaction with the debris disk surrounding the primary star.

2 OBSERVATIONS AND DATA REDUCTION

2.1 Clio2

We used the Clio2 1–5 μm camera (Sivanandam 2006) behind the new MagAO natural guide star AO system (Close et al. 2013) on the 6.5 m Magellan Clay telescope. MagAO/Clio2 is optimized for thermal IR wavelengths (3–5 μm), where star-to-planet contrast is minimized (Burrows et al. 1997). Clio2 has
a plate scale of 15.86 ± 0.05 mas pixel−1 and a field of view (FOV) of 5′′ × 16′′ in the magnification and subarray mode selected, based on 2013 April 7 astrometric observations of the central stars of the Trapezium (Close et al. 2012). There may be systematic errors from distortion of up to 0.4% in plate scale and 0.2 in rotation (based on Trapezium data). Data were obtained on 2013 April 4 and 12; conditions on both nights were photometric with winds of 7–11 m s−1 and seeing of 1′′ or less. Observations were taken in Angular Differential Imaging mode (ADI; Marois et al. 2006), with a two-position nod plus dither pattern (3′′–6′′ nods, ∼1′′ dithers). At each nod position, long science exposures and a short calibration frame were obtained. Further details are listed in Table 1. In the L′ data, the companion was only within the FOV in one of the two nod positions. In the J data, the companion was contaminated by an optical ghost in one of the nod positions; these data were discarded.

The data were processed with a custom reduction script and aperture photometry was used, following Bailey et al. (2013). The resulting images are shown in Figure 1. At separations of 0.3–3′′, we fit and removed the contribution from the stellar point-spread function (PSF) using principal component analysis (PCA) with 15 principal components, as described in Meshkat et al. (2013). To quantify the effect of PCA on point sources, artificial planets were injected into the raw data. The signal-to-noise ratio (S/N) of the recovered sources was determined following Bailey et al. (2013) and was used to infer the 5σ contrast as a function of separation. Our two-position nod observing strategy resulted in asymmetric sky coverage and thus decreasing sensitivity at increasing separations.

2.2. FIRE

We obtained an NIR spectrum of HD 106906 b on 2013 May 1 with the Folded-Port InfraRed Echellelette (FIRE; Simcoe et al. 2013) on the Baade 6.5 m Magellan telescope (Table 1). FIRE simultaneously captures 0.8–2.5 μm spectra with moderate resolution (R = 4800). The FIRE echelle slit is 7′′ long; we chose a slit width of 0′′.75 to accommodate the ∼0′′.8 seeing. Weather conditions otherwise were poor with high winds and thin clouds. The data were reduced using the FIRE reduction pipeline. A faint background contaminant, probably stellar, fell in the slit at a projected distance of ∼2.5′′, and was masked during processing. HD 106906 b was below the detection limit at λ < 1.25 μm in this short observation. Increasing sky and instrumental backgrounds decreased the data quality at λ > 2.25 μm. The resulting spectrum (binned to R ∼ 500) is presented in Figure 2; the S/N varies between three and six and is highest in the H band.

2.3. Ancillary Observations

To confirm the comoving status and red color of the candidate, we used archival data from Hubble Space Telescope Advanced Camera for Surveys (HST/ACS). ACS took coronagraphic observations on 2004 December 1 (program 10330, PI: H. Ford; see Table 1). We used World Coordinate System information encoded in the standard distortion-corrected ACS archive data products. The primary’s location beneath the coronagraphic mask was determined from its position relative to several background stars also seen in a non-coronagraphic acquisition frame; uncertainties in this measurement dominate the astrometric error budget. For photometric measurements of the companion, we analyzed the standard cleaned, flat-fielded ACS archive data products with the Starfinder PSF fitting routine and TinyTim synthetic PSF.

We also utilized Gemini/NICI data from 2011 March 21 (program GS-2011A-Q-44, PI: R. Jayawardhana; see Table 1). In this Kλ− and H−band snapshot program of young stars in the Sco-Cen association (Janson et al. 2013b), two images were obtained per target (long and short exposures). Multiple targets were observed consecutively, with the stars placed at different locations on the detector; we performed sky subtraction using exposures from the target observed immediately prior to HD 106906e. Images were flat-fielded using calibration data from 2011 March 30 and distortion-corrected using the polynomials provided by the observatory. The primary was saturated in both broadband Ks images, so we instead analyzed the narrowband H2 images.

3. ANALYSIS AND RESULTS

3.1. Photometry and Astrometry

We determine photometry for each dataset and sensitivity for the Clio2 L′ data. We find contrasts between the primary and companion of ΔL′ = 7.94 ± 0.05, ΔKs = 8.78 ± 0.06, and ΔJ = 10.7 ± 0.3 from Clio2 and ΔH2 = 8.70 ± 0.05 from NICI; the errors are dominant by sky/background noise. For the primary’s photometry, we use Two Micron All Sky Survey (2MASS) values at J, H, and Ks, presume H2 ∼ Ks, and interpolate between the 2MASS and WISE values at L′. Finally, we measure [606W′] = 24.27 ± 0.03 mag for the companion. All photometry is listed in Table 2. From our PCA reduction, we find L′ 5σ contrasts up to ∼10 mag (Figure 1).

Notes.

a) Exposure times for saturated/unsaturated images.
b) Because of nodding, field rotation, and/or optical ghosts, “b” was only visible and/or detected at high S/N in this subset of the data.

Table 1

| Date       | Inst. | Mode | Rot. (°) | Filter | Bandpass (μm) | Exposure (s) | Total Int. (min) |
|------------|-------|------|----------|--------|---------------|--------------|-----------------|
| 2013 Apr 4 | Clio2 | ADI  | 62       | L′     | 3.41–4.10     | 0.800/0.164a | 80 (19b)        |
| 2013 Apr 12| Clio2 | ADI  | 9        | J      | 1.17–1.33     | 30/0.164a    | 9 (4.5b)        |
| 2013 Apr 12| Clio2 | ADI  | 9        | Ks     | 2.00–2.30     | 0.280        | 7               |
| 2013 May 1  | FIRE  | Track | ... | J − Ks  | 1.0–2.5       | 120          | 8 (4p)          |
| 2004 Dec 1  | ACS   | Track | ... | F606W   | 0.47–0.71     | 2500         | 42              |
| 2011 Mar 21 | NICI  | Track | ... | H2     | 2.11–2.14     | 80.2/0.38a   | 1.3             |
| 2011 Mar 21 | NICI  | Track | ... | Ks     | 2.00–2.30     | 80.2/0.38a   | 1.3             |

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Three-epoch astrometry indicates that the companion is comoving. With Clio2, we find a projected separation ($\rho$) between the centroids of the primary and companion of $7.11 \pm 0.03$ arcsec at a position angle ($\theta$) of $307.3 \pm 0.2$. With NICI and ACS, we measure $\rho = 7.12 \pm 0.02$ arcsec and $\theta = 307.1 \pm 0.1$, and $\rho = 7.135 \pm 0.02$ arcsec and $\theta = 307.05 \pm 0.1$, respectively. The expected orbital motion for a circular, face-on orbit is $0.18$ arcsec, below our Clio2 astrometric precision.

The companion’s astrometry is inconsistent with the expected (and observed) motion of background objects at $>6\sigma$. The proper motion of HD 106906 is $-38.79 \pm 0.58$ mas yr$^{-1}$ and $-12.21 \pm 0.56$ mas yr$^{-1}$ in R.A. and decl., respectively (van Leeuwen 2007). Figure 1 shows the expected relative motion between the primary and a background object, along with astrometry for the companion and three background sources detected by both NICI and ACS (but not by Clio2).

### 3.2. Companion Properties

We constrain the companion’s spectral type, effective temperature, luminosity, and mass based on its NIR SED and its position in color–magnitude diagrams (CMDs). Figure 2 shows the companion’s NIR SED compared to both field brown dwarfs (BDs) and young Upper Scorpius (USco) BDs. All spectra are binned to a resolving power of $\sim500$, and normalized by the average $H$-band flux (unless otherwise noted). The companion’s
Figure 2. HD 106906 b NIR SED (black line) compared to old and young BD standards, normalized at the $H$-band unless otherwise noted. Left: field L0-L4 BDs. Right, top: USco L0-L2 BDs. Right, bottom: comparison of best-fit young and field templates, with each band independently normalized. The $H$-band spectrum is best matched by the triangular shape of a low surface-gravity L2-type, although its $K$-band spectrum is better fit by a field L3-type. We tentatively classify HD 106906 b as an intermediate-gravity L2.5 ± 1. The field objects are: 2MASSJ070746+2000AB, 2MASSJ020828+5442, Kelu-1AB, 2MASSJ1146+2230AB, and 2MASSJ2224-0058 (Cushing et al. 2005). The USco objects are: J160606-233513, J160723-221102, and J160603-221930 (Lodieu et al. 2008).

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

Table 2

| Property       | HD 106906 A | HD 106906 b |
|----------------|-------------|-------------|
| Distance (pc)$^a$ | 92 ± 6      |             |
| Age (Myr)$^b$     | 13 ± 2      |             |
| $V^b$            | 0.04 ± 0.02 |             |
| $T_{\text{eff}}$ | 6516 ± 165 $K^b$ | 1950 ± 200 $K^c$ |
|                  |              | 1800 ± 100 $K^d$ |
| Spectral type    | FSV$^b$     |             |
| log($L/L_\odot$) | 0.75 ± 0.06$^b$ | −3.64 ± 0.08 |
| Mass             | 1.5 ± 0.10 $M_\odot$ | 11 ± 2 $M_{\text{up}}$ |
| Separation (")   | 7.11 ± 0.03 |             |
| P.A. ("$^c$)    | 307.3 ± 0.2 |             |
| 606W             |             | 24.27 ± 0.03 |
| $J$              | 6.95 ± 0.03$^e$ | 17.6 ± 0.3   |
| $K_S$            | 6.68 ± 0.03$^e$ | 15.46 ± 0.06 |
| $H_S$            | 6.68 ± 0.05$^f$ | 15.38 ± 0.07 |
| $L'$             | 6.7 ± 0.1   | 14.6 ± 0.1   |
| W1$^g$           | 6.68 ± 0.04 |             |
| W2$^g$           | 6.68 ± 0.02 |             |
| W3$^g$           | 6.59 ± 0.02 |             |
| W4$^g$           | 4.66 ± 0.03 |             |

Notes.

$^a$ Hipparcos catalog (van Leeuwen 2007).

$^b$ Pecaut et al. (2012).

$^c$ Effective temperature from field dwarf scale.

$^d$ Effective temperature from evolutionary models.

$^e$ 2MASS $J$/$H$/$K_S$ survey. Unresolved.

$^f$ Assumed equal to 2MASS $K_S$.

$^g$ WISE survey. Unresolved.

$H$-band spectrum is somewhat triangular, and indeed it is best matched by a young L2-type dwarf. Its $K$-band spectrum, however, is rounded, more akin to that of an older field L3-type dwarf. We therefore tentatively classify HD 106906 b with an intermediate surface-gravity L2.5 ± 1. However, a higher S/N spectrum (including the gravity-sensitive alkali lines in $J$ band) must be obtained to confirm this classification.

We estimate the companion’s mass by using a $K$-band bolometric correction (BC$_K$) to derive its luminosity, which may be compared to that predicted by the “hot start” COND (cloud-free) and DUSTY (cloudy) evolutionary models (Baraffe et al. 2003; Chabrier et al. 2000). We do not consider “cold start” models, because formation by core accretion is impossible at hundreds of AU, and scattering into the current orbit is disfavored (Section 3.5). A field L2.5 ± 1 object has $T_{\text{eff}} = 1950 ± 200$ K and BC$_K = 3.32 ± 0.13$ (Golimowski et al. 2004). Applying the field BC$_K$ yields log($L/L_\odot$) = −3.64 ± 0.08. From the evolutionary models, this corresponds to a mass of 11 ± 2 $M_{\text{up}}$ and $T_{\text{eff}}$ of 1800 ± 100 K, using an age of 13 ± 2 Myr. Even if the system is the mean age of LCC, 17 Myr, the companion remains 13 $M_{\text{up}}$.

We also investigate the companion’s properties using CMDs at $J$, $K_S$, and $L'$ (Figure 3). For context, we plot the DUSTY and COND evolutionary model tracks as well as the photometry of field M- and L-type dwarfs (Leggett et al. 2010) and other DI low-mass companions. Note that the Leggett et al. (2010) photometry is $K$-band, which is typically ~0.1 mag brighter than $K_S$ for low-mass objects. In $J$ versus $L'$, the companion falls on the DUSTY track, near several other low-mass companions ($\beta$ Pic b, κ And B, 2M0103 B, and 1RXS 1609 b). However, it is much brighter than these objects at $K_S$, falling blue-ward of the COND track, more similar to the $K - L'$ color of early-to mid-L field dwarfs. This behavior may echo that of the HR 8799 planets and 2M1207 b, which also become blue at $K_S$.

3.3. Bound Companion or Free-floating Cluster Member?

We calculate the probability that HD 106906 b is not bound, but instead a free-floating cluster member with similar proper motion, by estimating the space density of free-floating BDs in
LCC. Because the census of BD cluster members is incomplete, we extrapolate their space density from the known B star population. We take the 44 known B star cluster members from the Hipparcos catalog (de Zeeuw et al. 1999), plus an additional eleven likely members, which we believe were spuriously rejected from the catalog because their space motions are perturbed by binary companions. Assuming the census of B stars is complete, a Kroupa initial mass function (Kroupa 2001) predicts a total stellar population of 1836 stars above 0.08 $M_\odot$.

We next scale the total stellar population by an assumed BD fraction. Surveys of young clusters have found $N_{\text{BD}}/N_{\text{star}} \sim 0.2$ (e.g., Slesnick et al. 2004; Luhman 2007). If LCC has a similar ratio, then it should contain $\sim 370$ BDs below 0.08 $M_\odot$. Most cluster members are concentrated within $\sim 500$ deg$^2$ (de Zeeuw et al. 1999). HD 106906 is one of two LCC members observed in our disk-selected program,\(^9\) hence the probability of a chance alignment within 7$^\prime$ is $< 1 \times 10^{-5}$. We conclude that HD 106906 Ab is most likely a bound pair.

3.4. Constraints on Additional Companions

No additional point sources are detected in our $L'$ image. We could detect additional companions as massive as “b” at projected separations $> 0'.38$, reaching a background limit as low as 4 $M_{\text{Jup}}$ (based on COND models). At larger separations, we achieve a sensitivity of 5–7 $M_{\text{Jup}}$. Two low S/N NICI sources ($\rho = 9'.6$, $\theta = 236^\circ$ and $\rho = 7'.1$, $\theta = 76^\circ$) do not have counterparts in the HST or Chio2 images (the first is not within the Chio2 $L'$ FOV). The sources have $K_\beta = 19.5–20$, based on their contrast with HD 106906 b. From the available data, we cannot determine the nature of either faint NICI source.

3.5. Circumstellar Disk Properties and Companion–Disk Interaction

HD 106906 was selected for DI because it has a large IR excess indicative of a massive debris disk, and because the shape of the excess’ SED suggests the disk is devoid of both hot and warm material. Chen et al. (2005) derived a color temperature of 90 K and $L_{\text{IR}}/L_\star = 1.4 \times 10^{-3}$ from 24 and 70 $\mu$m broadband photometry. With the addition of Spitzer Infrared Spectrograph and MIPS-SED spectra, we confirm that the disk emission is well fit by a blackbody temperature of 95 K, using data up to $\sim 100$ $\mu$m.

As the disk is not resolved at any wavelength, we estimate its plausible extent from the dust temperature. Given the stellar parameters of HD 106906 A (Table 2), the inferred dust location is $\sim 20$ AU, assuming blackbody-like grains. The inner radius ($r_{\text{in}}$) could be as close as 15 AU for silicate grains with radii of 10 $\mu$m. Using a sample of nine Herschel resolved disk images around early-type stars, Booth et al. (2013) showed that the measured disk sizes are 1–2.5 times larger than the blackbody estimates. The discrepancy increases toward later spectral types, reaching a factor of 6 for a G5V-type host (Wyatt et al. 2012). Given the primary’s F5V spectral type, the outer radius of the disk ($r_{\text{out}}$) is likely to be < 120 AU. We adopt a model with a 20–120 AU dust ring for the following discussion. Future resolved imaging is required to determine the true extent of the disk.

The HD 106906 system adds to a small but growing sample of DI planetary systems with debris disks. It has been suggested that the planets in these systems play a hand in sculpting their debris disks (e.g., HR 8799, β Pic, HD 95086: Su et al. 2009; Lagrange et al. 2010; Moor et al. 2013). HD 106906 b could similarly be shepherding the disk around its primary star if it is on an eccentric orbit; a massive companion will disrupt disk

\(^9\) Interestingly, the other system, HD 95086, also hosts a DI planetary-mass companion (Rameau et al. 2013).
material between its Hill sphere at periastron and its Hill sphere at apastron. To gravitationally sculpt the disk’s outer edge at 120 AU, the companion’s periastron must be 135 AU. Presuming it is at apastron now, the orbit would require an eccentricity of 0.65. If the disk’s outer radius is smaller, the companion is not currently at apastron, or the orbit is inclined relative to our line of sight, the necessary orbital eccentricity would increase.

Two formation mechanisms are typically postulated for wide planetary-mass companions: in situ formation (binary-star-like) or formation in a tight orbit followed by scattering to a wide orbit (planet-like). Scattering from a formation location within the current disk is unlikely to have occurred without disrupting the disk in the process (Raymond et al. 2012). We also note that the perturber must be $>11 M_{\text{Jup}}$; we do not detect any such object beyond 35 AU (Section 3.4), disfavoring formation just outside the disk’s current outer edge. While it is possible that the companion is in the process of being ejected on an inclined trajectory from a tight initial orbit, this would require us to observe the system at a special time, which is unlikely. Thus we believe the companion is more likely to have formed in situ in a binary-star-like manner, possibly on an eccentric orbit ($\sim$ 20 AU and $r_{\text{out}} \lesssim 120$ AU. The companion would require an orbital eccentricity $>0.6$ to gravitationally sculpt the outer edge of this disk. The presence of a massive disk around the primary argues against a scattering origin for the companion. We suggest it is more likely to have formed in situ in a binary-star-like process, though $M_{\text{b}}/M_{\star} < 1\%$ is unusually small.

HD 106906 A was targeted because it hosts a massive, ring-like debris disk, potentially sculpted by a planetary companion. From the disk’s SED, we estimate $r_{\text{in}} \sim 20$ AU and $r_{\text{out}} \lesssim 120$ AU. The companion would require an orbital eccentricity $>0.6$ to gravitationally sculpt the outer edge of this disk. The presence of a massive disk around the primary argues against a scattering origin for the companion. We suggest it is more likely to have formed in situ in a binary-star-like process, though $M_{\text{b}}/M_{\star} < 1\%$ is unusually small.

HD 106906 b joins a growing sample of widely separated, planetary-mass and BD companions whose formation mechanisms are poorly understood. Each additional example is valuable, particularly when additional environmental information is present (such as the existence and morphology of a circumstellar disk). Future scattered light or submillimeter observations of the HD 106906 circumprimary disk might uncover signs of dynamical instabilities and further constrain the system’s formation process.

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