A 5 μm IMAGE OF β PICTORIS b AT A SUB-JUPITER PROJECTED SEPARATION: EVIDENCE FOR A MISALIGNMENT BETWEEN THE PLANET AND THE INNER, WARPED DISK

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ABSTRACT

We present and analyze a new M′ detection of the young exoplanet β Pictoris b from 2008 VLT/NaCo data at a separation of ≈4 AU and a high signal-to-noise rereduction of L′ data taken in 2009 December. Based on our orbital analysis, the planet’s orbit is viewed almost perfectly edge-on (i ≈ 89 deg) and has a Saturn-like semimajor axis of 9.50 AU−3.91AU. Intriguingly, the planet’s orbit is aligned with the major axis of the outer disk (Ω ≈ 31 deg) but is probably misaligned with the warp/inclined disk at 80 AU, often cited as a signpost for the planet’s existence. Our results motivate new studies to clarify how β Pic b sculpts debris disk structures and whether a second planet is required to explain the warp/inclined disk.

Key words: planetary systems – stars: early-type – stars: individual (β Pictoris)

Online-only material: color figures

1. INTRODUCTION

Two decades of studies have argued that the nearby, 12 Myr old A-type star β Pictoris likely harbors a young planetary system (e.g., Smith & Terri 1984; Kalas & Jewitt 1995; Mouillet et al. 1997); recently, Lagrange et al. (2009a, 2010) detected a ≈9 ± 3 MJ planet around this star (β Pic b). Imaged at projected separations of ∼6 AU and ∼8 AU (2003 November and 2009 October–December, respectively), β Pic b—with long with HR 8799e (Marois et al. 2010; Currie et al. 2011)—may also provide a more direct comparison to the solar system’s gas giants than other directly imaged planets which are at wider separations (e.g., Fomalhaut b and HR 8799bcd; Kalas et al. 2008; Marois et al. 2008). Current studies have yet to detect the planet at projected separations ≤0.3 (Lagrange et al. 2009b; Fitzgerald et al. 2009). Data at these smaller separations could provide crucial constraints on the planet’s orbit.

Imaging planets at small, ≲0.3′′, separations requires significantly reducing quasi-static speckle noise and wavefront errors induced by imperfect AO corrections. Advanced observing/image processing techniques like angular differential imaging (ADI) coupled with point-spread function (PSF) subtraction from a locally optimized combination of images (LOCI) algorithm (Marois et al. 2006; Lafreniere et al. 2007) significantly attenuate speckles and increase sensitivity. New instrumentation, such as the Gemini Planet Imager (GPI; Macintosh et al. 2008), will achieve far superior wavefront control. Generally, these efforts focus on planet imaging in the near-IR. However, mid-IR imaging naturally overcomes some of these challenges as the achievable Strehl ratio is better and the planet-to-star contrast is most favorable. High-contrast imaging with Strehl ratios ≥0.9 can yield at least some planet detections close to the telescope diffraction limit (e.g., 2 λ/D for HR 8799d; Serabyn et al. 2010). Because M-band imaging often achieves these high Strehl ratios (Minowa et al. 2010; Hinz et al. 2006), it may be a promising route for detecting very young and self-luminous planets at small λ/D separations, despite a much higher sky background.

In this Letter, we report a detection of β Pic b at a separation of ∼0.21 extracted from archival M′-band Very Large Telescope (VLT)/NaCo data taken in 2008 November. We also present a high signal-to-noise L′ detection of β Pic b from 2009 December data first published in Lagrange et al. (2010). We combine these data with recent data from Bonnefoy et al. (2011) and Quanz et al. (2010) to better constrain the orbit and atmosphere of β Pic b.

2. OBSERVATIONS AND DATA

Our study originates from the need to test the ADI/LOCI reduction pipeline first presented in Currie et al. (2010) and updated in Currie et al. (2011) at separations smaller than those where the pipeline had previously extracted planet signals (r < 0.375). Because β Pic b’s reported projected separation in 2009 was ≈0.3′′ (Lagrange et al. 2010), we chose the now publicly available Lagrange et al. L′-band data from 2009 December 29 to test our code performance. Lagrange et al. (2010) discuss the details of the L′-band observations. The total field rotation in units of the image FWHM was ∼3 λ/D, sufficient for using our reduction pipeline.

Figure 1 (top-left panel) shows our processed L′-band image using the LOCI algorithm in annular regions of 250 × FWHM (N4 = 250) with reference images selected from frames with at least 0.5 × FWHM field rotation (δ = 0.5). The planet is easily detected and is well separated from residual speckle noise. The planet signal-to-noise, determined from the dispersion in pixel intensity values in concentric annuli, is S/N ≈ 21, about a factor of 4–5 greater than from Lagrange et al. (2010).

Motivated by this success, we searched for additional β Pic data in the VLT/NaCo archive taken in ADI mode between 2003 and 2009, finding a set taken on 2008 November 11 with the L27 camera. Most of these data were taken in sparse aperture masking (SAM) mode in the Ks and L′ modes over a span of ≈4 hr: these data were mentioned in Lagrange et al. (2009b) as not providing good constraints on the companion. However, we found ∼13 minutes of the M′ data taken in ADI mode without
aperture masking at various times in between the masking data. Over the course of the entire observing sequence, the parallactic angle changed by $\sim 100$ deg, or $\sim 2.4–3\,\lambda/D$ at $0.2–0.25$: sufficient for image processing with our pipeline.

Basic image processing of the $M'$-band data followed the steps outlined in Currie et al. (2011). After registering each image and subtracting off the smooth seeing halo, we Fourier filtered the data to remove residual low spatial frequency noise and masked any hitherto unidentified bad pixels previously lost in the seeing halo. We explored a range of LOCI parameter space, varying $\delta$, $N_A$, and the ratio of the radial to azimuthal lengths of the subtraction annulus ($g$). Because $\beta$ Pic b is very luminous in the mid-IR (e.g., $\Delta L' \approx 7.7$; Lagrange et al. 2010; and Section 3 of this work), we focused on “aggressive” LOCI settings of $\delta = 0.25–0.5$, $N_A = 200–300$, and $g = 0.3–1$, which better remove residual speckle noise.

Figure 1 (top-right panel) shows our best reduced $M'$ image. $\beta$ Pic b is clearly detected in the southwest quadrant $\sim 0'.2–0'.25$ from the star ($S/N \approx 6$). Manually inspecting each image between the radial profile subtraction and final image combination steps and examining a signal-to-noise map of the median-combined image also shows that the peak does not result from latent image artifacts. Slightly different settings for $\delta$, $N_A$, and $g$ also yield significant detections (bottom panels).

3. ANALYSIS

Our new $M'$-band detection and high signal-to-noise $L'$-band detection allow new constraints on the planet’s orbit. To derive precise astrometry needed to investigate the planet’s orbit, we adopt the NaCo plate scale and orientation for the L27 camera from Bergfors et al. (2011): 27.1 mas pixel$^{-1}$ and a north position angle of $-0.6$ deg. These values are nearly identical to those for the L27 camera quoted by Lagrange et al. (2009a) for 2003 NaCo data and for the S27 camera from Ehrenreich et al. (2010) calibrated from Trapezium data acquired closest in time to the $\beta$ Pic data: our astrometric results do not leverage on which calibration we use.

To fine tune our measurements, we correct for the photometric and astrometric biases induced by LOCI processing by comparing the imputed fluxes and positions of fake point sources added to registered images with computed fluxes and centroid positions obtained after LOCI processing (e.g., Lafreniere et al. 2007; Thalmann et al. 2009; Currie et al. 2011). While we lack unsaturated data from this run to directly confirm the PSF shape, unsaturated $M'$ data taken in prior runs such as that for HD 158882 (2007 March) show that the AO-assisted NaCo $M'$ PSF core is axisymmetric and well reproduced by a simple Gaussian intensity distribution. For the $L'$-band data, the astrometric bias is minimal, whereas $\beta$ Pic b’s measured radial separation in $M'$ band is biased by about $+0.5$ pixels (0'.013). The position angle offsets for both data are minimal.

We determine the $M'$-band position to be at a separation of $r = 0'.210 \pm 0'.027$ and position angle of $211.49 \pm 1.9$ deg. The $L'$-band position is at $0'.326 \pm 0'.013$ and $210.64 \pm 1.2$ deg (Table 1). Here we conservatively assume an uncertainty in radial separation of one pixel for the $M'$ band and 0.5 pixels for the (higher signal-to-noise) $L'$-band data. The position angle uncertainty—determined from the dispersion in values using different centroiding estimates (e.g., cntrd.pro versus gcenrd.pro)—is 0.5 pixels (0.7 mas$\times r$), or 1.2 and 1.9 deg for $L'$ and $M'$, comparable to uncertainties for $\beta$ Pic b by Lagrange.
et al. (2009a, 2010) and Bonnefoy et al. (2011). Assuming that β Pic is at a distance of 19.3 pc (Criçio et al. 1997), the planet was at a projected separation of 4.05 ± 0.50 AU on 2008 November 11 and 6.29 ± 0.25 AU on 2009 December 29.

To determine the range of allowable orbits for β Pic b, we followed the method described in Janson et al. (2011) used to model the orbit of the low-mass brown dwarf companion GJ 758 B (Thalmann et al. 2009; Currie et al. 2010), which is to model the orbit of the low-mass brown dwarf companion we follow the method described in Janson et al. (2011) used to model the orbit of the low-mass brown dwarf companion GJ 758 B (Thalmann et al. 2009; Currie et al. 2010), which is somewhat similar to earlier analyses for β Pic b (Lagrange et al. 2009b; Fitzgerald et al. 2009). In this approach, we perform a Monte Carlo simulation comparing the astrometry to predictions from randomly selected orbits, where we allow all orbital parameters to vary. The minimum χ² value in our simulation is χ²~1.23. Given our data’s weak constraints on the orbital acceleration and the degenaracies due to the unknown line-of-sight components of planet position and velocity, no single “best” orbital solution emerges. Rather, the best-fitting solutions describe an extended, well-defined family of solutions that all match the data equally well. We choose a cut of χ²~2.23 (χ²~<χ²_{min}+1) to represent the family of best-fitting orbits. We also consider the results for a cut of χ²~<8 (χ²~<χ²_{max}+1) to represent the family of best-fitting orbits. From the set of models satisfying this criterion, we determine the median value of each parameter, weighted by the ratio of the mean to current orbital velocity for the corresponding orbit, and identify the weighted 68% confidence interval about the median. We include astrometry from the highest signal-to-noise data separated in time by more than ~3 months (Table 1).

Table 1

| Astrometry Date | Filter | Separation (") | Position Angle (°) | Reference |
|-----------------|--------|----------------|-------------------|-----------|
| 2003 Nov 10     | L′     | 0.411 ± 0.008  | 31.7 ± 1.3        | Lagrange et al. (2009a) |
| 2008 Nov 11     | M′     | 0.210 ± 0.027  | 211.49 ± 1.9      | This work |
| 2009 Dec 29     | L′     | 0.326 ± 0.013  | 210.64 ± 1.2      | This work |
| 2010 Mar 20     | Kₜ     | 0.345 ± 0.012  | 209.8 ± 0.8       | Bonnefoy et al. (2011) |

Notes. Our astrometry and photometry data are drawn from the three separate reductions shown in Figure 1. The L′ measurement assumes L′_β, Pic = 3.45. The M′ photometry lacks reliable photometric calibration and thus is not useful for astrometric modeling.

Unfortunately, the M′-band observations of β Pic were taken with the star saturated within ~3 pixels (~0.6 FWHM) of the centroid and there were likewise no unsaturated standard star observations. We derive a very crude magnitude estimate by scaling the M′ PSF of HD 158882 to the unsaturated portion of the β Pic PSF and use HD 158882’s known brightness (Kₜ = 5.09; Kₜ-M′ ~ 0) to calibrate β Pic b’s brightness. We estimate ΔM′~ 8.02 ± 0.50 (M′_M~ 9.99), where we consider the uncertainties in our PSF fitting scaling, the dispersion in individual planet magnitude estimates drawn from separate reductions, and the intrinsic signal-to-noise of our detection. We determine an L′ contrast of ΔL′~ 7.71 ± 0.06. Combining the L′ measurement with the Kₜ band and [4.05] data from Bonnefoy et al. (2011) and Quanz et al. (2010), we have three good quality photometric points to investigate the family of possible solutions for β Pic b’s atmospheric properties.

Figure 4 compares the β Pic b photometry to best-fit spectra for models with log(g) = 3.5/4/4.5 and T_{eff} = 1000–1800 K for a range of cloud prescriptions: the Model A and AE thick cloud prescriptions, respectively, from Currie et al. (2011) and Madhusudhan et al. (2011) that best fit the HR 8799 planet spectral energy distributions, the Model E cloud deck prescription appropriate for brown dwarfs (Burrows et al. 2006), and a cloudless atmosphere. The χ² values for these models are, respectively, χ²_A ≈ 24.8, 12.3, 20.4, and 43.2 for Models A, AE, and the cloudless case. The AE thick cloud model provides the best fit. Thick cloud models also produce redder L′-M′ colors at high temperatures, similar to that estimated here (≈−0.22 ± 0.50), though our lack of a reliable M′ photometric calibration precludes strong conclusions. Good photometry is available in only three filters, so we cannot yet say whether β Pic b has thick clouds like the HR 8799 planets (Currie et al. 2011; Madhusudhan et al. 2011).

The range of gravities and effective temperatures are log(g) = 3.5–4.5 and T_{eff} = 1400–1800 K. The implied masses for these models range between 4.1 M_J and 19.2 M_J and the ages range between 1 and 27 Myr, broadly consistent with the planet mass (9 ± 3 M_J; Lagrange et al. 2010), stellar age (12 Myr; Zuckerman et al. 2001), and likely formation timescale (≤3–5 Myr; Currie et al. 2009). Planet fluxes in the near-IR (1–1.65 μm) and the 3–3.5 μm methane absorption trough are
highly sensitive to cloud structure (e.g., Currie et al. 2011; Madhusudhan et al. 2011). Thus, $J$ or $H$ broadband data and/or narrowband 3–3.5 $\mu$m data will be critical in breaking model fitting degeneracies.

4. DISCUSSION

We present a new detection of $\beta$ Pic b in the $M'$ band at a separation of $\sim 0\prime.21$ ($a_{\text{projected}} = 4.05$ AU) from archival VLT/NaCo data taken in 2008 November and a high S/N re-reduction of $L'$ data first reported by Lagrange et al. (2010), using these data to constrain the planet’s orbit and atmospheric properties. For orbits whose fit to the data yield $\chi^2 \leq 2.23$, we find that the $\beta$ Pic planet has a semimajor axis of $a_p = 10.99$ AU $^{-1.81}$. Au and a moderate/low eccentricity ($e \lesssim 0.31$). Admitting orbital solutions with $\chi^2 \leq 8$, the parameter ranges are $a_p = 9.50$ AU $^{+3.93}$ and $e \lesssim 0.23$. In both cases, values for the planet’s inclination ($i \sim 88.06$–89.69 deg) and longitude of ascending node ($\Omega \sim 50.56$–52.12 deg) are tightly constrained and imply that the planet’s orbit is almost perfectly aligned with the outer debris disk, but not with the inclined inner disk ($\Omega \sim 35$–36 deg). We cannot extract reliable photometry from our $M'$-band data; new data at 1–1.65 $\mu$m and 3–3.5 $\mu$m are needed to constrain $\beta$ Pic b’s atmosphere.

Numerous studies of the $\beta$ Pic debris disk(s) have identified the star as harboring a young planetary system (e.g., Smith & Terrile 1984; Kalas & Jewitt 1995; Mouillet et al. 1997; Weinberger et al. 2003). More recently, the presence of a warp in the disk at $\sim 80$ AU—due to the combined effects of the main disk with PA $\sim 30.8$ and a second, inclined disk offset by 5 deg—was identified as a clear signpost of a perturbing planet (e.g., Mouillet et al. 1997; Heap et al. 2000; Golimowski et al. 2006), motivating high-contrast imaging studies to image the planet. Lagrange et al. (2009a) identified $\beta$ Pic b as a likely source of the inclined disk and used the disk morphology to derive mass estimates (see also Lagrange et al. 2010).
Our results suggest that β Pic b is probably not aligned with the inner disk/warp but rather with the main disk, as the allowed range in Ω is offset from the main disk as measured by Kalas & Jewitt (1995) by no more than ~ 1 deg. Furthermore, the planet may be misaligned with the submillimeter disk emission (Wilner et al. 2011), which is sensitive to dynamical sculpting by planets (Kuchner & Stark 2010). However, models accounting for the inclined inner disk presume that the planet’s orbit is also inclined relative to the main disk (e.g., Mouillet et al. 1997; Augereau et al. 2001). New β Pic b astrometry, a more precise astrometric calibration of existing β Pic NaCo data by determining and correcting for image distortion, and a detailed relative calibration between NaCo data and data revealing the disk will further clarify how β Pic b’s orbital plane compares to that for the main disk and the inner disk/warp. Furthermore, our new orbital constraints for β Pic b strongly motivate new studies of the dynamical sculpting of β Pic’s debris disk by planets. If β Pic b or non-planet related mechanisms (e.g., Armitage & Pringle 1997) fail to explain the inclined debris disk/warp, the existence of additional planets in the system may be required.

Our M’-band detection demonstrates that it is possible to directly image planets at separations approaching the telescope diffraction limit without SAM interferometry (Ireland & Kraus 2008). The high Strehl ratio, large amount of field rotation, large mid-IR planet brightness, and LOCI processing pipeline are the keys to closing this gap. While SAM can detect planets interior to the telescope diffraction limit, it is overall less sensitive. However, the techniques can be complementary, yielding detections or robust limits on infant gas giant planets around the youngest stars on ~ 5–100 AU scales.

Upcoming facilities such as GPI, SPHERE, SCExAO, and Project 1640 achieve higher contrast at small inner working angles in the near-IR primarily through more sophisticated wavefront control (Macintosh et al. 2008; Beuzit et al. 2008; Martinache & Guyon 2009; Hinkley et al. 2011). Our results, coupled with previous L’-band detections of β Pic from Lagrange et al. (2009a, 2010) and the high signal-to-noise L’-band detection of HR 8799e (Marois et al. 2010), suggest that the mid-IR may also be fertile ground for new exoplanet detections at small separations for very young systems. Young, nearby 1.5–2 M⊙ stars like β Pic are particularly promising targets for direct imaging surveys (e.g., Crepp & Johnson 2011) and many have resolved debris disks (e.g., HD 181327; Schneider et al. 2006; Chen et al. 2008). Imaging massive planets in such systems can yield additional studies of planet–disk interactions, such as those motivated by this work.

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