THE GEMINI NICI PLANET-FINDING CAMPAIGN: THE ORBIT OF THE YOUNG EXOPLANET \( \beta \) PICTORIS b

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ABSTRACT

We present new astrometry for the young (12–21 Myr) exoplanet \( \beta \) Pictoris b taken with the Gemini/NICI and Magellan/MagAO instruments between 2009 and 2012. The high dynamic range of our observations allows us to measure the relative position of \( \beta \) Pictoris b with respect to its primary star with greater accuracy than previous observations. Based on a Markov Chain Monte Carlo analysis, we find the planet has an orbital semi-major axis of \( 9.1^{+5.3}_{-3.5} \) AU and orbital eccentricity \(<0.15 \) at 68\% confidence (with 95\% confidence intervals of 8.2–48 AU and 0.00–0.82 for semi-major axis and eccentricity, respectively, due to a long narrow degenerate tail between the two). We find that the planet has reached its maximum projected elongation, enabling higher precision determination of the orbital parameters than previously possible, and that the planet’s projected separation is currently decreasing. With unsaturated data of the entire \( \beta \) Pictoris system (primary star, planet, and disk) obtained thanks to NICI’s semi-transparent focal plane mask, we are able to tightly constrain the relative orientation of the circumstellar components. We find the orbital plane of the planet lies between the inner and outer disks: the position angle (P.A.) of nodes for the planet’s orbit (211.8 ± 0.3) is 7.4\% greater than the P.A. of the spine of the outer disk and 3.2\% less than the warped inner disk P.A., indicating the disk is not collimation relaxed. Finally, for the first time we are able to dynamically constrain the mass of the primary star \( \beta \) Pictoris to 1.76\(^{+0.18}_{-0.11}\) \( M_\odot \).

Key words: planetary systems – planet–disk interactions – planets and satellites: detection – stars: individual (\( \beta \) Pictoris)

Online-only material: color figures

1. INTRODUCTION

\( \beta \) Pictoris is a young (\( \sim 12–21 \) Myr; Barrado y Navascués et al. 1999; Zuckerman et al. 2001; Binks & Jeffries 2014), nearby (19.44 pc; van Leeuwen 2007) A6 star that hosts one of the most prominent known debris disks (e.g., Smith & Terrile 1984; Wahhaj et al. 2003; Weinberger et al. 2003; Golimowski et al. 2006; Lagrange et al. 2012a). The disk midplane is warped, with a 4\(^\circ\) offset between the inner warped disk and the outer main disk, suggesting a giant planet influencing the disk (Mouillet et al. 1997). This planet \( \beta \) Pictoris b was first detected in data from 2003, and the planet reappeared on the other side of the star in 2009 (Lagrange et al. 2009, 2010). \( \beta \) Pictoris b is one of the first planets to be directly imaged and has the smallest projected physical separation of any imaged planet to date. With a contrast of 9 mag at \( \lambda_\text{K}_s \) band and a current projected separation of \( \sim 0.4 \) AU, the planet is challenging to detect even with state-of-the-art adaptive optics.

Orbital properties of directly imaged planets can encode clues to their formation. The eccentricities of these planets, for example, may trace migration or planet–planet interactions (e.g., Takeda & Rasio 2005; Jurić & Tremaine 2008; Wang & Ford 2011). \( \beta \) Pictoris b represents the longest-period exoplanet whose full orbital parameters can be determined with present observations. The estimated orbital period of \( \sim 20 \) yr allows us the opportunity to determine the orbit of this planet, whereas most other directly imaged planets will require many more decades of observations for a robust orbit determination. The orbital parameters of \( \beta \) Pictoris b are of particular interest since they allow us to study the relationship between the planet and the debris disk.

The Gemini NICI Planet-Finding Campaign was a four-year survey to detect extrasolar planets conducted between 2008 and 2012 (Liu et al. 2010; Nielsen et al. 2013; Wahhaj et al. 2013b; Biller et al. 2013). In addition to detecting a number of brown dwarf companions (Biller et al. 2010; Wahhaj et al. 2011; Nielsen et al. 2012), we detected the planet \( \beta \) Pictoris b at multiple epochs over the course of the Campaign. We combine these observations with new data from Magellan MagAO and previous work to determine the orbit of the planet.

2. OBSERVATIONS

VLTI/NACO: Chauvin et al. (2012) present nine epochs of \( \beta \) Pictoris b astrometry from VLTI NACO, between 2003 and 2011. Bonnefoy et al. (2013) present an additional epoch from 2012 January, as well as an improved orbital fit. We use the 10 astrometric observations and errors as reported in these works.

Gemini-South/NICI: We observed \( \beta \) Pictoris b with NICI at Gemini-South at four epochs between 2009 and 2012 (Table 1). Reductions were performed with the Gemini NICI Planet-finding Campaign pipeline, described in detail in Wahhaj et al. (2013a). These data are discussed in detail in Males et al. (2014),
which also includes a comparison to an independent analysis of some of the data by Boccaletti et al. (2013). We find that for overlapping epochs there is good agreement between the NICI and NACO astrometry, indicating that there is no significant astrometric offset between the two instruments. In addition, NICI measurements have smaller uncertainties compared to those from NACO: the median separation and P.A. uncertainties are 0.005 and 0.6 for NICI and 0.011 and 1.81 for NACO. This increased precision is due to the partially transparent focal plane mask of NICI, which allows for an accurate measurement of the location of the star relative to the planet. Bonnefoy et al. (2013) note the primary source of error in their astrometry is the uncertainty in the position of the star.

Magellan/MagAO: β Pic b was observed on UT 2012 December 4 in the Ys (0.985 μm) filter of Magellan MagAO+VisAO, and on UT 2012 December 1, 2, 4, and 7 in the 3.1 μm, 3.3 μm, L′, and M′ filters of Magellan MagAO+Clio2. The astrometry and photometry from MagAO+VisAO is described in detail in Males et al. (2014) and from MagAO+Clio2 in K. M. Morzinski et al. (2014, in preparation). Similar to NICI, the Magellan MagAO+VisAO instrument has a partially transmissive focal plane mask so the primary star is unsaturated in the data. MagAO+Clio2 data in 3.1 μm, 3.3 μm, L′, and M′ were taken with long and short exposures of saturated and unsaturated data, while M′ data were entirely short unsaturated exposures.

The VisAO astrometry calibration is tied to the wider field of view Clio2 camera, and the two cameras are mounted simultaneously on the same rotator so they will have some common systematics, but the observations of the planet by these two cameras are otherwise independent measurements. To calibrate the Clio2 astrometry, we observed the Trapezium Cluster in the Orion Nebula as a reference. Over the nights of 2012 December 3, 4, 6, and 8 UT, we locked the AO loop on either θ¹ Ori B or C. Stars θ¹ Ori A and E were also in the fields, as were many fainter Trapezium stars (see K. M. Morzinski et al. 2014, in preparation for details). We compared the positions of the stars to their positions in Close et al. (2012) to derive the platescale, instrument angle, and distortion solution. We applied these solutions to our β Pic data to calibrate them. The position of the planet was then measured in the Clio2 images by a grid search over (x, y) positions.

3. MCMC ORBIT FITTING

3.1. Methods

We use a Metropolis–Hastings Markov Chain Monte Carlo approach to fit orbital parameters to the astrometric motion of β Pic b from 2003 to 2012, following the procedure of Ford (2005, 2006). Such an approach has previously been applied to astrometric orbits by, e.g., Liu et al. (2008) and Dupuy et al. (2010) for substellar companions, as well as by Chauvin et al. (2012) and Bonnefoy et al. (2013) for β Pic b itself. We compute two types of fits: one with the total system mass fixed (as done by all previous published orbital fits) and another with the total mass as a free parameter. For the fixed-mass case, we have six free parameters: the semi-major axis (a), eccentricity (e), inclination angle (i), argument of periastron (ω), position angle of nodes (Ω), and the epoch of periastron passage (T0). The period (P) is determined from the semi-major axis using Kepler’s Third Law and adopting a total system mass of 1.75 M⊙ (Crifo et al. 1997). For the floating-mass fit, the orbital period is the seventh free parameter, so the total mass is allowed to take on any value.

At the start of the chain, initial values are chosen for each free parameter. A proposed trial step is taken by choosing a displacement in all parameters by randomly drawing from six (or seven) Gaussians centered on the current parameters with fixed standard deviations. The probability ratio between current and proposed orbit parameters is computed by determining the difference in the χ² statistic (∆χ²) for all astrometric epochs for β Pic b between the initial and trial sets of parameters. The choice of whether to adopt the trial parameters as the new step or to retain the current set is made via the Metropolis–Hastings algorithm with probability ratio ∝ e−Δχ²/2. Nonphysical parameters (a ≤ 0, P ≤ 0, e < 0, e ≥ 1) are assigned a χ² of 10⁶ while the three viewing angles (i, ω, Ω) and epoch of periastron passage (T0) are allowed to take any values without limits. To ensure the chains run efficiently, the standard deviations of the Gaussians for choosing trial steps are chosen initially via an algorithm with probability ratio

| Instrument | Filter | Sep. (″) | P.A. (°) | Epoch (UT) |
|------------|--------|---------|----------|------------|
| Gemini/NICI | CHaS (4%) | 0.323 ± 0.010 | 209.3 ± 1.8 | 2009 Dec 3 |
| Gemini/NICI | CHaL (4%) | 0.339 ± 0.010 | 209.2 ± 1.7 | 2009 Dec 3 |
| Gemini/NICI | Ks | 0.407 ± 0.005 | 212.9 ± 1.4 | 2010 Dec 25 |
| Gemini/NICI | CHaS (1%) | 0.455 ± 0.003 | 211.9 ± 0.4 | 2011 Oct 20 |
| Gemini/NICI | Kc | 0.452 ± 0.005 | 211.6 ± 0.6 | 2011 Oct 20 |
| Gemini/NICI | CHaS (1%) | 0.447 ± 0.003 | 210.8 ± 0.4 | 2012 Mar 29 |
| Gemini/NICI | Kc | 0.448 ± 0.005 | 211.8 ± 0.6 | 2012 Mar 29 |
| Magellan/MagAO+Clio2 | 3.1 μm, 3.3 μm, L′, M′ | 0.461 ± 0.014 | 211.9 ± 1.2 | 2012 Dec 2 |
| Magellan/MagAO+VisAO | Ys | 0.470 ± 0.010 | 212.0 ± 1.2 | 2012 Dec 4 |
Figure 1. Marginalized distributions of orbital parameters from our MCMC fit to the orbit of \( \beta \) Pic b, for the cases where the total mass of the system is fixed at 1.75 \( M_\odot \) (red solid lines) and floating as a free parameter (blue dotted lines). The distributions have been normalized so that their peaks are unity. Dashed lines mark the median of each distribution, and green points and error bars denote the position angle of the outer main disk and inner warped disk, without the overall astrometric calibration error of 0\(^\circ\)2 that is common to the measurement of the planet and the two disks. Since the orbital fit draws on data from different instruments, the PDF for position angle of nodes does include the absolute astrometric uncertainties, though (as expected) the uncertainty on the PDF is less than the uncertainty for the P.A. measurement at any epoch. (A color version of this figure is available in the online journal.)

parameter space near \( \Omega = 212^\circ \), the results are equally valid for \( \Omega = 32^\circ \).\(^{10}\)

Ten chains are run from the same starting parameters so that we may test for convergence using the Gelman–Rubin (GR) statistic, with \( 10^8 \) steps per chain and parameters saved every 1000 steps. The GR statistic is essentially the ratio of the variance in each parameter in individual chains to the total variance for all chains. If each chain is sampling the same region of parameter space then the GR metric will be very close to unity. If the chains are still exploring different regions of parameter space when the chains are terminated, then the GR statistic will be significantly larger than 1. A GR statistic less than 1.1 indicates the chains are converging, while less than 1.01 means excellent convergence (Ford 2006).

3.2. Results

We present medians and confidence intervals for each parameter in the fixed-mass case in Table 2. The inclination angle, argument of periastron, position angle of nodes, and epoch of periastron passage have a GR statistic less than 1.01, and the other two parameters have a GR statistic less than 1.1, indicating that our posterior distributions for all parameters are reliable.

Figure 1 displays the resulting marginalized posterior probability distributions for the orbital parameters and total system mass for both the fixed-mass and floating-mass cases. Figure 2 shows an example set of orbital parameters from the fixed-mass MCMC chains that has the lowest \( \chi^2 \) within the 68% confidence region for all parameters (\( \chi^2_r = 1.38 \)).

Our results for the fixed-mass case show an orbit with semi-major axis of about 9 AU is favored, with inclination angle and position angle of nodes (the two angles that describe the
With a uniform prior on eccentricity, we find $e < 0.2)\) and we expect future observations to be most consistent with larger values of semi-major axis corresponding to more eccentric orbits. Given the presence of the disk, it is unlikely that the orbit of the planet is significantly noncircular ($e \gtrsim 0.2), and we impose a prior that the eccentricity must be smaller than 0.2, $e < 0.15$ at 68% confidence and $e < 0.72$ at 95% confidence. If we were to impose a prior that the eccentricity must be smaller than 0.2, we would obtain $a = 8.9^{+0.8}_{-0.3}$ AU and $P = 20.1^{+2.5}_{-1.2}$ yr, with the distributions for the other parameters about the same as in the uniform prior case. Our MCMC results find a median of the distributions for the other parameters about the same as in the uniform prior case. Our MCMC results find a median of the time of maximum elongation (when the projected star–planet separation reaches a maximum) of 2012.63 and 68% (95%) confidence interval between 2012.55 (2012.48) and 2012.70 (2012.79). Our Magellan epochs are after turnaround time in 99% of all orbits. So while the Magellan data represent the largest separation between star and planet in our astrometric record, our orbit fitting results indicate that maximum elongation was reached prior to these data being taken.

Finally, we consider the floating-mass MCMC fit. Though generally less constrained than the fixed-mass fit, the posterior mass distribution (lower right panel of Figure 1) shows that the previous estimated mass of $1.75 M_\odot$ is well within the 68% confidence interval. While additional astrometry is required to place a more precise limit on the mass of the star $\beta$ Pic, this total mass distribution of $1.6 \pm 0.3 M_\odot$ indicates that our orbital fit and existing astrometric measurements are reasonable. Semi-major axis and period are highly correlated in our floating-mass fit, and while the chains have not converged for the semi-major axis and period individually (GR statistics of 1.2), the GR statistic for mass is 1.0012, indicating a reliable measurement of the mass. If we were to impose the prior that $e < 0.2$ in the floating-mass case, our mass constraints for $\beta$ Pic would slightly tighten to $1.7 \pm 0.2 M_\odot$. Similarly, the semi-major axis range would shrink from $24^{+51}_{-15}$ AU to $9.0^{+0.9}_{-0.6}$ AU. The minimum $\chi^2$ reached in the floating-mass chain (41.64) is similar to that for the fixed-mass chain (41.67).

Crifo et al. (1997) estimate the mass of $\beta$ Pic by comparing the position of the star on the HR diagram to theoretical evolutionary tracks, finding a good fit for masses between 1.7 and 1.8 $M_\odot$. Blondel & Dje (2006) derive a similar mass, between 1.65 and 1.87 $M_\odot$, again from evolutionary models and the HR diagram. Our dynamical mass is independent of any evolutionary model and so provides independent confirmation of the mass of the star, and indicates these previous estimates were accurate.

### 3.3. Comparison to Previous Fits

We now compare our results to previously published MCMC orbital fits. Comparing our posteriors to the results from Chauvin et al. (2012), we have similar distributions for semi-major axis and eccentricity but tighter constraints on the viewing angles of the orbit. For inclination angle and position angle of nodes, we find $88.9 \pm 0.7$ and $211.8 \pm 0.3$ compared to $88.5 \pm 1.7$ and $212.6 \pm 1.5$ from Chauvin et al. We find similar distributions in semi-major axis and eccentricity, though with smoother posteriors indicating our MCMC chains are better converged. (Chauvin et al. do not provide GR values for their fit but state that their GR statistics are consistent with convergence.) Since the preferred orbits from our chains are close to circular (68% having eccentricity less than 0.15), the argument of periastar and epoch of periastar passage are poorly defined as they were for Chauvin et al., since it is difficult to determine periastar in a near-circular orbit. Nevertheless, the two values are tightly correlated (bottom right panel of Figure 3). While the location of periastar is not well-defined, the location of the planet at a particular epoch between $\sim 2000$ and $\sim 2020$ is.

Bonnefoy et al. (2013) refit the orbit with data from Chauvin et al. (2012) as well as an additional VLT data point from 2012 and find similar results, with MCMC chains that appear more converged than those of Chauvin et al. (2012). The semi-major axis from this fit is reported to be within $8–10$ AU at 80% confidence; we find a less constrained semi-major axis, with

Table 2
Orbital Parameters of $\beta$ Pic b

| Parameter                          | Lowest $\chi^2$ | Median | 68% CI            | 95% CI            | GR Stat. |
|-----------------------------------|-----------------|--------|-------------------|-------------------|----------|
| Semi-major axis (AU)              | 9.6             | 9.1    | 8.6–14.4          | 8.2–48.0          | 1.0827   |
| Eccentricity                      | 0.08            | 0.08   | 0.02–0.40         | 0.00–0.82         | 1.0580   |
| Inclination angle (°)             | 88.8            | 88.9   | 88.2–89.6         | 87.4–90.4         | 1.0006   |
| Argument of periastar (°)         | 6.5             | –8     | –102–85           | –167–166          | 1.0022   |
| Position angle of nodes (°)       | 211.9           | 211.8  | 211.5–212.1       | 211.2–212.4       | 1.0011   |
| Epoch of periastar passage        | 2012.88         | 2012   | 2009–2019         | 2006–2023         | 1.0021   |
| Period (yr)                       | 22.60           | 21     | 19–41             | 18–251            | …        |

Floating-Mass

| Parameter                          | Fixed-Mass      |           |                 |                 |          |
|-----------------------------------|-----------------|-----------|------------------|------------------|----------|
| Semi-major axis (AU)              | 83.6            | 24.3      | 9.1–75.2         | 8.4–96.7         | 1.2512   |
| Eccentricity                      | 0.90            | 0.65      | 0.11–0.89        | 0.01–0.91        | 1.2473   |
| Inclination angle (°)             | 89.2            | 89.0      | 88.3–89.7        | 87.6–90.3        | 1.0047   |
| Argument of periastar (°)         | 347.4           | –16       | –46–1            | –133–116         | 1.0067   |
| Position angle of nodes (°)       | 211.6           | 211.7     | 211.4–211.9      | 211.2–212.3      | 1.0115   |
| Epoch of periastar passage        | 2011.52         | 2011      | 2010–2013        | 2006–2021        | 1.0012   |
| Period (yr)                       | 581.53          | 96        | 22–516           | 18–758           | 1.2282   |
| Mass ($M_\odot$)                  | 1.73            | 1.64      | 1.37–1.95        | 1.13–2.38        | 1.0012   |

Notes. Results from the MCMC fit to the orbit of $\beta$ Pic b and orbital parameters for the lowest $\chi^2$ within the 68% confidence interval from the chains (Figure 2). The final column gives the Gelman–Rubin statistic for each parameter: values closer to unity indicate a higher degree of convergence.
80% confidence lying between 8 and 14 AU. We also find a wider range of eccentricities that fit the data, with 80% confidence $e < 0.35$ compared to $e < 0.15$ reported by Bonnefoy et al. (2013). Conversely, we find tighter constraints on the orientation of the orbit on the sky. From their Figure 8, we determine that their inclination angle distribution is centered on 88°.7 with an FWHM of 3°.5, and their distribution for the position angle of nodes is centered on 212° and FWHM of 2°.7. Our distributions for these parameters have similar centers of 88°.9 and 211°.8, but with smaller FWHMs of 1°.7 and 0°.7.

After our paper was submitted, Macintosh et al. (2014) presented an additional measurement of the position of β Pic b on 2013 November 18 UT, measuring $0.434 \pm 0.006$ and $211.8 \pm 0.5$, using the Gemini Planet Imager (GPI) at Gemini-South. They fit this new data point along with the VLT astrometry presented in Chauvin et al. (2012). Their astrometric coverage thus has a three-year gap between early 2011 and late 2013, and a data point one year later than the orbital coverage we present here. They find generally similar results for the orientation of the orbit, $\Omega = 211.6 \pm 0.45$ and $i = 90.69 \pm 0.68$, compared to the $211.8 \pm 0.3$ and $88.9 \pm 0.7$ we present here. The peaks of their distributions for the semi-major axis and eccentricity are similar to ours, but their posteriors do not reveal the same narrow degenerate tail toward large eccentricity and large semi-major axis. (Note that Macintosh et al. 2014 plot 10%, 50%, and 90% confidence contours for their orbit fitting results, while we show 68.3%, 95.4%, and 99.7% contours.)

When we fit their data (the combination of the Chauvin et al. 2012 and the GPI astrometry) with our MCMC method, we do not reproduce the posteriors of Macintosh et al. (2014) and still see the same long eccentricity tail. In fact, the lowest chi-square orbit reached in the chain is in this tail ($\chi^2 = 0.45$), with semi-major axis 47.8 AU and eccentricity of 0.81. The cause of this discrepancy is most likely the choice of priors, as a nonuniform prior on eccentricity can make high eccentricity orbits sufficiently unlikely so that the chain never leaves the low-period, low-eccentricity region of parameter space. For other orbital parameters, including inclination angle (with a reflection about 90°) and position angle of nodes, we precisely reproduce the 68% confidence intervals given by Macintosh et al. (2014).

Finally, we combine our data set with the additional GPI astrometry point and re-fit the orbit. We find similar parameters
for the fixed-mass case as we present here, $a = 9.4^{+11.8}_{-6.0}$ and $e = 0.09^{+0.49}_{-0.06}$, with the same degenerate tail toward long periods and large eccentricities as before. We find slightly smaller error bars for inclination angle and position angle of nodes, $i = 89.1 \pm 0.6$ and $\Omega = 211.4 \pm 0.24$. While the 68% confidence intervals are largely unchanged for these parameters, in the floating-mass case we significantly reduce the uncertainty on the mass of $\beta$ Pic, $M = 1.76^{+0.18}_{-0.17} M_\odot$, reaching 10% precision on the mass of the star.\footnote{Using our MCMC fit to the data set presented here (VLT, NICI, and Magellan data) we predict astrometry on 2013 November 18 of $0.415 \pm 0.007$ and $212.3 \pm 0.6$, within 1.5 and 0.1$\sigma$ of the GPI measurements, respectively. For the floating mass case the predicted positions are $0.424 \pm 0.019$ and $212.3 \pm 0.6$. The uncertainty in our predictions and the GPI measurement errors are similar for the fixed mass case, though with a slight offset in separation, so it is not surprising that adding the GPI data point to this analysis does not produce substantially different results. For the floating mass case, however, the prediction uncertainty for separation is three times larger than the measurement error, so the new point does noticeably refine the fit.}

4. DISK–PLANET ALIGNMENT

In order to compare the position angle of the orbit to the disk, we perform a custom reduction of our 2011 NICI data to recover the disk. We begin by removing the azimuthally averaged profile of the point spread function from the individual images, as described in Wahhaj et al. (2013a) except that the running azimuthal average used here is taken over 90 pixels instead of 30 pixels. This process removes large-scale (>90 pixels or 1′62) azimuthal structure from both the stellar halo and the disk. Since the $\beta$ Pic disk is known to be edge-on, this procedure does not alter the disk profile significantly. After this step the disk reduction then proceeds with our standard ADI pipeline.

The signal-to-noise maps of the reduced images for the $\text{CH}_4 L$ and $K_{\text{cont}}$ filters are shown in Figure 4. The north/east (NE) and south/west (SW) extensions of the disk were considered separately. As a function of radius we fit two Gaussians to the azimuthal disk profile, taking a 20 AU width at each sampling and stepping by 1 AU. We compute the median position angles
for the two sides of the outer disk (between 60 and 120 AU) of 209.21 ± 0.05 and 28.79 ± 0.06. The inner disk is only visible within 90 AU, and we find median values of the position angle between 60 and 90 AU of 212.99 ± 0.07 and 32.28 ± 0.07. These are errors in the fit only and do not include uncertainty in the direction of true north of 0.2, as we are concerned only with the relative offset between the orbital plane of the planet and the position angle of the disk. We present these values along with relative and absolute errors in Table 3.

To ensure that our reduction process has not biased these measurements we simulate the disk as a series of rings given the fit to the data, and then create a simulated data set with the same set of rotation angles in our ADI data set (a total range of 42°) to model self-subtraction. The offset between the initial model and the measurements of the self-subtracted simulation was much smaller than 0.1, and so this effect is not the dominant source of error. Rather it is residuals from the stellar point spread function that dominate the measurement of the disk position angle.

Our P.A. measurements are consistent with the cADI two-component fit reported by Lagrange et al. (2012a), who find 29.07+0.20−0.19 and 209.00+0.16−0.15 for the outer disk. Our measurements of offsets between the outer and inner disk of 3.78 ± 0.12 (SW) and 3.49 ± 0.13 (NE) are also close to the Lagrange et al. (2012a) cADI value of 3.9+0.6−0.4. Unlike Lagrange et al. (2012a), where the position of the center of the star is uncertain, the partially transmissive focal plane mask of NICI allows us to precisely measure the star position in images of the disk.

Using our position angle for the SW disk of 209.21 ± 0.05, our measurement of the position angle of nodes of the orbit of 211.8 ± 0.3 is 7.4σ discrepant with the position angle of the outer disk. The inner warped disk has a position angle of 212.9 ± 0.07, which is discrepant at the 3.2σ level. Thus, we find the planet’s orbital plane is not aligned with either disk.

Currie et al. (2011) presented a preliminary orbit based on four astrometric points (the bare minimum needed for an orbit fit) and a non-MCMC method and found the position angle of nodes to be between the two disks. When we apply our MCMC method to their data we find generally larger uncertainties in orbital parameters than Currie et al. (2011) report. Using an MCMC fit to their data, we find the position angle of nodes to be 210.9 ± 0.9, 1.8σ greater than the outer disk P.A. and 2.2σ less than the inner disk P.A. Chauvin et al. (2012) and Bonnefoy et al. (2013) fit more data with a similar MCMC method to ours and find the orbital plane of the planet to be consistent with the inner disk (Ω = 212.6 ± 1.5 and Ω = 212.0 ± 1.1, respectively, both within 1σ of the P.A. of the inner disk). By including our higher precision astrometric data and longer time baseline, we find the position angle of nodes to be between the two disks, though closer to the inner disk.

5. DISCUSSION

We now consider the implications of a misalignment between β Pic b and the two disks. Our observations recall a dynamical picture of the β Pic disk recently painted by Dawson et al. (2011). If a planet on an inclined orbit (inclination ip) is introduced into a disk of noninteracting particles with zero initial inclination, the secular theory of Laplace–Lagrange (e.g., Murray & Dermott 1999) shows us that the inclinations of the particles will oscillate about ip, creating a cuspy disk structure with apparent inclination 2ip in its inner regions. Our measurement that the planet’s inclination is intermediate between the two observed disk planes seems to support this picture. In contrast, earlier simulations by Mouillet et al. (1997) and Augereau et al. (2001) yielded a disk coplanar with the planet.

| Disk Component | P.A.   | Relative Error | Absolute Error |
|----------------|--------|---------------|----------------|
| NE Outer (60–120 AU) | 28.79  | 0.06          | 0.3            |
| SW Outer (60–120 AU)  | 209.21 | 0.05          | 0.3            |
| NE Inner (60–90 AU)   | 32.28  | 0.07          | 0.3            |
| SW Inner (60–90 AU)   | 212.28 | 0.07          | 0.3            |

Figure 4. Signal-to-noise maps of our Gemini NICI observations of β Pic from 2011 showing both disk and planet in CH4 S (left) and Kcont (right). The figure is oriented with north up and east to the left. The black circle marks the location of the planet.

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

Table 3

Disk Measurements of β Pic
One important assumption built into the Dawson et al. (2011) model and supported by our observations is that the planetesimals are not yet collisionally relaxed (collisional relaxation in debris disks is the gradual process by which planetesimals lose energy and exchange momentum via collisions so that the distribution of their orbits approaches a steady state), as models of structure in other debris disks have assumed (e.g., Quillen 2006; Rodigas et al. 2014). Another important assumption built into the Dawson et al. (2011) model is that the planet is introduced instantaneously, fully formed, at time zero. We infer that the β Pic disk is probably not collisionally relaxed; this inference should yield some interesting constraints on models of the collisional evolution of planetesimals in debris disks (e.g., Nesvold et al. 2013). Moreover, if the Dawson et al. (2011) model is indeed correct, it appears that the β Pic planet was introduced to its current orbit suddenly compared to the secular timescale, perhaps scattered there by another planet.

This notion begs us to ponder the role of multiple planets in sculpting the disk. In the context of their model, Dawson et al. (2011) placed severe limits on the presence of a second planet in the system disturbing the disk. In addition, Absil et al. (2013) exclude a second planet more massive than ~5 M_{Jup} outside of 0.2 a based on L′ high contrast images of β Pic. But what caused the inclination of β Pic b if not an interaction with another massive planet? And how did the planetesimals respond to this interaction? These questions remain unanswered.

Finally, we consider the transit event noted by Lecavelier Des Etangs et al. (1995) in 1981 November and find very loose constraints on a transit of the planet given the available data. We search for such a transit by finding the smallest projected distance between star and planet between 2015 and 2019 and then subtract one or two orbital periods from the returned epoch for each step in our MCMC chains, choosing the epochs that are closest to 1981. We find the most recent closest approach to be at epoch 2007.44^{+0.14}_{-0.17} (crossing behind the star), with the next closest approach (possible transit) to take place in 2017.59^{+0.09}_{-0.18} adopting the orientation of the orbit from the RV measurements of Lagrange et al. (2012b) and Snellen et al. (2014). The median value for the epoch of closest approach one or two orbital periods earlier than 2017 is 1977.52, with a 68% confidence interval between 1971.07 and 1982.14 (95% confidence interval from 1976 and 1993, given the long tail of the posterior for the orbital period). The smallest projected distance from star to planet is less than 31 times the radius of β Pic (1.8 ± 0.2 R_⊕; Di Folco et al. 2004) at 68% confidence (~<51 times the radius at 95% confidence). Thus we cannot rule out a transit with the current orbital fit. Lecavelier Des Etangs et al. (1995) and Chauvin et al. (2012) speculate that the transit event may not be caused by the planet itself but rather by solid material entrained by the planet and carried in its Hill sphere. We cannot rule out this possibility either, and more data are required. We predict that the next transit will take place between 2017.41 and 2018.18 at 68% confidence (2017.27–2019.19 at 95% confidence), with a median epoch of 2017.59. Additional astrometric observations in the next few years will provide a more precise transit window and transit probability.

6. CONCLUSIONS

We have examined the orbit of β Pic b given five new epochs of data taken with Gemini NICI and Magellan/MagAO, finding a semi-major axis of 9.1^{+5.3}_{-5.0} AU and a period of 21^{+21}_{-1} yr. The astrometric record of β Pic b is now long enough to be able to remove the assumption of the total system mass, which was needed by all previous fits to this orbit. When we solve for the mass of β Pic itself we find a value of 1.76^{+0.18}_{-0.17} M_☉, consistent with the expected value of 1.75 M_☉. The position angle of nodes for our fixed-mass orbit is offset from the observed position angles of the inner warped disk (at 3.2σ significance) and from the outer disk (at 7.4σ significance), suggesting that the disk is not collisionally relaxed.

Numerous degenerate orbital solutions exist for astrometric data that show minimal acceleration during the timeframe of the observations, in particular between the semi-major axis, period, and eccentricity. Observing significant acceleration, and in particular the reversal of direction at maximum elongation, greatly reduces these degeneracies. Our orbital fit indicates that the planet has reached maximum elongation and is currently moving back toward the star, crossing to the other side of the star by ≈2018. β Pic b has been observed extensively since its reappearance in 2009 and the current window for studying the planet will remain open for just a few more years before the planet is undetectable behind the star again. Advanced planet-finding instruments such as GPI and SPHERE will likely allow for orbital monitoring of the planet closer to the star, so the time of lost contact is likely to be significantly shorter than it was between 2003 and 2009. The window for the next transit is between 2017.41 and 2018.18 at 68% confidence, and future astrometric monitoring will provide a more precise prediction to guide photometric monitoring.

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