MAGELLAN ADAPTIVE OPTICS FIRST-LIGHT OBSERVATIONS OF THE EXOPLANET $\beta$ PIC b. I. DIRECT IMAGING IN THE FAR-RED OPTICAL WITH MagAO+VisAO AND IN THE NEAR-IR WITH NICI$^*$

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ABSTRACT

We present the first ground-based CCD ($\lambda < 1 \mu$m) image of an extrasolar planet. Using the Magellan Adaptive Optics system’s VisAO camera, we detected the extrasolar giant planet $\beta$ Pic b in Y-short ($\lambda_y$, 0.985 $\mu$m), at a separation of 0.470 ± 0.010 and a contrast of (1.63 ± 0.49) × 10$^{-3}$. This detection has a signal-to-noise ratio of 4.1 with an empirically estimated upper limit on false alarm probability of 1.0%. We also present new photometry from the Gemini Near-Infrared Coronagraphic Imager instrument on the Gemini South telescope, in CH$_{15.1}$% (1.58 $\mu$m), $K_s$ (2.18 $\mu$m), and $K_{cont}$ (2.27 $\mu$m). A thorough analysis of our photometry combined with previous measurements yields an estimated near-IR spectral type of L2.5 ± 1.5, consistent with previous estimates. We estimate $\log(L_{bol}/L_{\odot}) = -3.86 \pm 0.04$, which is consistent with prior estimates for $\beta$ Pic b and with field early-L brown dwarfs (BDs). This yields a hot-start mass estimate of 11.9 ± 0.7 $M_{\text{Jup}}$ for an age of 21 ± 4 Myr, with an upper limit below the deuterium burning mass. Our $L_{bol}$-based hot-start estimate for temperature is $T_{\text{eff}} = 1643 \pm 32$ K (not including model-dependent uncertainty). Due to the large corresponding model-derived radius of $R = 1.43 \pm 0.02$ $R_{\text{Jup}}$, this $T_{\text{eff}}$ is ∼250 K cooler than would be expected for a field L2.5 BD. Other young, low-gravity (large-radius), ultracool dwarfs and directly imaged EGPs also have lower effective temperatures than are implied by their spectral types. However, such objects tend to be anomalously red in the near-IR compared to field BDs. In contrast, $\beta$ Pic b has near-IR colors more typical of an early-L dwarf despite its lower inferred temperature.

Keywords: brown dwarfs – instrumentation: adaptive optics – planetary systems – planets and satellites: detection – planets and satellites: individual (beta Pictoris b) – stars: individual (beta Pictoris)

Online-only material: color figures

1. INTRODUCTION

In contrast to the stellar main sequence, brown dwarfs (BDs) form a true evolutionary sequence. Such BDs are not massive enough to maintain a constant effective temperature ($T_{\text{eff}}$) via hydrogen fusion ($M \lesssim 0.075 M_{\odot}$, e.g., Burrows et al. 1997). Thus, a BD cools as it ages, radiating away the gravitational potential energy from its formation (Burrows et al. 2001). The BDs are classified into spectral types by comparison to anchor objects. Various clues to classification were judiciously chosen such that they should correspond to temperature, at least in a relative sense (Kirkpatrick et al. 1999; Burgasser et al. 2002, 2003). Temperature is not a readily observable quantity, however, it is well established from theory that substellar objects ranging in mass from $\sim 1$ to $\sim 75 M_{\text{Jup}}$ will have a radius in a narrow range of 0.8–1.1 $R_{\text{Jup}}$ (e.g., Burrows et al. 2011; Fortney et al. 2007). This means that bolometric luminosity, $L_{bol} = 4\pi \sigma_b R^4 T_{\text{eff}}^4$, is approximately determined by temperature alone. $L_{bol}$ is observable, so with our theoretical understanding of radius we can infer $T_{\text{eff}}$ and find that field BD spectral types appear to be a well-defined temperature sequence (Golimowski et al. 2004; Stephens et al. 2009), except perhaps for the coolest objects (Dupuy & Kraus 2013). The result is that the spectral type (SpT) of a BD is a function of both mass and age.

The situation is even more challenging for young objects, which have not completed postformation contraction. The radius of such an object can be significantly larger, depending on how it formed (Burrows et al. 1997; Chabrier et al. 2000; Baraffe et al. 2003; Marley et al. 2007; Spiegel & Burrows 2012). Young objects will also have lower mass than older objects of the same temperature. With lower mass and larger radius these young objects have lower surface gravity (low-g), which changes their spectral morphology (e.g., Lucas et al. 2001; Kirkpatrick et al. 2006), but even so their spectra can generally be classified within the ultracool dwarf sequence (Cruz et al. 2009; Allers & Liu 2013).

This population of such low-g BDs is especially interesting because they potentially serve as analogs for young extrasolar giant planets (EGPs). Many of the best-studied low-g BDs are companions, such as AB Pic B (Chauvin et al. 2005b) and...
2M0122 B (Bowler et al. 2013). Examples of isolated low-g objects are 2M0355 (Faherty et al. 2013) and PSO318.5 (Liu et al. 2013b). These objects tend to have fainter near-IR absolute magnitudes (Faherty et al. 2013; Liu et al. 2013a) and have $T_{\text{eff}}$ several hundred K cooler than field BDs of the same SpT (Bowler et al. 2013; Liu et al. 2013b). These low-g BDs also tend to be much redder in near-IR colors, and despite being fainter in the bluer filters and having lower $T_{\text{eff}}$, their bolometric luminosities tend to be consistent with the field for their spectral types (Liu et al. 2013b).

The first handful of directly imaged planets show similar properties, highlighting the challenges of studying substellar objects in the new physical regime of low-g. For instance, the EGP HR 8799 b and the planetary mass companion 2M1207 b have L-dwarf-like very red near-IR colors, but their luminosities and inferred temperatures (800–1000 K) are more like mid-T dwarfs (Chauvin et al. 2005a; Marois et al. 2008). This has been interpreted as a consequence of the gravity dependence of the L–T transition (Metcalf & Hillenbrand 2006). Thick dust clouds, which cause the redward progression of the L-dwarf sequence as temperature drops, persist to even lower temperatures at low-g (Skemer et al. 2011; Barman et al. 2011b; Marley et al. 2012). In this framework, the extremely red and underluminous HR 8799 b and 2M1207 b are objects that have yet to make the transition to the cloudless, bluer, T-dwarf sequence, hence they are often thought of as extensions of the L-dwarf sequence (Bowler et al. 2010; Barman et al. 2011a; Madhusudhan et al. 2011).

The directly imaged EGP $\beta$ Pic b, in contrast, is much hotter, and its near-IR spectral energy distribution (SED) is much more typical when compared to field and low-g BDs (Lagrange et al. 2010; Quanz et al. 2010; Bonnefoy et al. 2011; Currie et al. 2011a; Bonnefoy et al. 2013; Currie et al. 2013). $\beta$ Pic b is unique among the directly imaged EGPs in that we have a dynamical constraint on its mass from radial velocity (RV). A complete orbit has not yet been observed, so RV monitoring constrains the mass depending on the semimajor axis ($a$): for $a < 8$, $9$, $10$, $11$, $12$ AU the upper mass limit is $M < 10$, $12$, $15.5$, $20$, $25$ $M_{\odot}$, respectively (Lagrange et al. 2012). The astrometry currently favors $8 \lesssim a \lesssim 9$ AU (Chauvin et al. 2012), hence $M \lesssim 12$ $M_{\odot}$, though larger values are not ruled out. We can expect to have a good dynamical understanding of $\beta$ Pic b’s mass in the near future.

$\beta$ Pic b is also noteworthy in that we have relatively good constraints on the age of its primary star. The age of the $\beta$ Pictoris moving group, of which $\beta$ Pic A is the eponymous member, has recently been revised upward to about 21 ± 4 Myr (Binks & Jeffries 2013) using the lithium-depletion boundary technique. Though somewhat larger than the earlier age estimate of $12^{+8}_{-4}$ Myr by Zuckerman et al. (2001), these two estimates are consistent at the 1σ level.

A well-determined age and a dynamical mass constraint make $\beta$ Pic b a valuable benchmark for understanding the formation and evolution of both low-mass BDs and giant planets. Here we present the bluest observations of $\beta$ Pic b from the first light of the Magellan Adaptive Optics (MagAO) system, using its visible wavelength imager VisAO. We also present detections with the Gemini Near-Infrared Coronagraphic Imager (NICI). In Section 2, we describe MagAO and VisAO and briefly discuss calibrations of this new high-contrast imaging system. In Section 3, we present our observations and data reduction procedures. We analyze the 0.9–2.4 $\mu$m SED of $\beta$ Pic b in Section 4, showing that this EGP looks like a typical early-L dwarf. We explore the ramifications of this for the physical properties ($L_{\text{bol}}$, mass, $T_{\text{eff}}$, and radius) of the planet. Then in Section 5, we compare these derived properties to field objects and discuss the relationship of the measured characteristics of EGPs and BDs. Finally, we summarize our conclusions in Section 6.

2. THE MAGELLAN VisAO CAMERA

MagAO is a 585 actuator adaptive secondary mirror (ASM) and pyramid wavefront sensor (PWFS) adaptive optics (AO) system, installed at the 6.5 m Magellan Clay Telescope at Las Campanas Observatory (LCO), Chile. The system is a near-clone of the Large Binocular Telescope (LBT) AO systems (Esposito et al. 2010, 2011). MagAO has two science cameras: the Clio2 15 $\mu$m camera (Freed et al. 2004; Sivanandam et al. 2006) and the VisAO 0.5–1 $\mu$m camera. Here we describe characterization and calibration of VisAO relevant to this report. For additional information about MagAO see Close et al. (2012a), Males et al. (2012), and Kopon et al. (2013). For additional information about the on-sky performance of VisAO see Close et al. (2013), Follette et al. (2013), and Wu et al. (2013). High-contrast imaging of $\beta$ Pic b in the thermal-IR with Clio2 is presented in our companion paper (K. M. Morzinski et al. 2014, in preparation, hereafter Paper II).

2.1. The $Y_S$ Filter

Because this was the first attempt to conduct high-contrast observations with VisAO, we used our longest wavelength bandpass to maximize Strehl ratio (SR) and flux from the thermally self-luminous planet. We refer to this filter as “Y-short,” or $Y_S$. For a complete characterization of this filter see Appendix A. In brief, it is defined by a long-pass dichroic at 950 $\mu$m and the CCD QE cutoff at $\sim$1.1 $\mu$m. Including a representative atmosphere in the profile, the central wavelength of $Y_S$ is 0.985 $\mu$m and the width is 0.086 $\mu$m.

2.2. The VisAO Antiblooming Occulting Mask

The VisAO camera contains a partially transmissive occulting mask, used to prevent saturation of the CCD when observing bright stars. The mask has a radius equivalent to about 0.′1 were it in the focal plane, but it is approximately 60 mm out of focus in an f/52 beam. This has two consequences of note here. The first is that the mask has an apodized attenuation profile that extends to $\sim$0.′8 in radius, so at a separation of $\sim$0.′46, $\beta$ Pic b is under the mask. The second, and more challenging, consequence is that the mask attenuation will depend on wavefront quality. We did not fully characterize the mask using $\beta$ Pic itself, so we bootstrapped an attenuation profile from other measurements at different levels of wavefront quality. We describe this process in detail in Appendix B. We estimate that the mask transmission at the separation of $\beta$ Pic b was $0.60^{+0.05}_{-0.10}$.

2.3. Astrometric Calibration

In Close et al. (2013), we describe the calibration of plate-scale in several filters and North orientation of the VisAO camera. Here we describe our calibrations in $Y_S$ and how we tied VisAO to the Clio2 astrometry. The primary stars used for VisAO calibration were 0′ Ori B1 and B2 in the Trapezium. These stars were observed repeatedly and with a separation...
of \(\sim0'94\) B2 are well within the isoplanatic patch when guiding on B1. Close et al. (2013) recently showed that all four stars in \(\theta^1\) Ori B are exhibiting orbital motion, so we measured their current astrometry using the wider field of view (FOV) Clio2 camera. A complete description of these measurements is provided in Paper II. In brief, we used combinations of Trapezium stars to measure the distortion, plate-scale, and orientation of Clio2. This was done using the recent astrometry given in Close et al. (2012b), which used LBT AO/Pisces to measure the distortion, plate-scale, and orientation of Clio2. We then compared measurements of B1 and B2 with Clio2 to those with VisAO. This was done in 2012 December in the \(Y_5\) filter with the occulting mask out of the beam. The extra glass added by the mask substrate changes the focus position slightly, decreasing the plate-scale. We measured this change in 2013 May also using \(\theta^1\) Ori B1 and B2. The ratio of plate-scales with and without the mask is \(0.9972 \pm 0.0003\). This was applied to the \(Y_5\)-open plate-scale to determine the \(Y_5\)-mask plate-scale.

We also determined the orientation of the CCD with respect to north, which we denote by NORTH\(_{\text{VisAO}}\). Our images are derotated counterclockwise using the equation DEROT\(_{\text{VisAO}}\) = ROTOFF + \(90^\circ\) + NORTH\(_{\text{VisAO}}\), where ROTOFF is the rotator offset, equal to rotator angle plus parallactic angle. The astrometric calibration of VisAO is summarized in Table 1.

By dithering \(\theta^1\) Ori B around the detector we diagnosed a slight focal plane tilt, which causes a small change in plate-scale, \(<1\%\), from top to bottom predominantly in the y-direction (Close et al. 2013). At the \(\sim0'47\) separation of \(\beta\) Pic b this change in plate-scale amounts to less than 1 mas, so we neglect it.

### 3. OBSERVATIONS AND DATA REDUCTION

#### 3.1. VisAO

We observed \(\beta\) Pic with VisAO on the night of 2012 December 4 UT in the \(Y_5\) filter using the 50/50 beam splitter, sending half the \(\lambda < 1\) \(\mu m\) light to the PWFS. The image rotator was fixed to facilitate angular differential imaging (ADI; Liu 2004; Marois et al. 2006). Conditions were photometric. V-band seeing, as measured by a colocated differential image motion monitor (DIMM), varied from \(\sim0'45 \sim0'75\) during the 4.17 hr of elapsed time included in these observations.

#### 3.1.1. VisAO Point-spread Function and Strehl Ratio

Towards the end of the observation we took off-mask calibration data to assess AO performance and calibrate our photometry. We took 1061 0.283 s frames off the occulting mask, at airmass 1.14. V-band seeing as measured by the DIMM was \(\sim0'65\) during these measurements. To avoid saturation this data was taken in our fastest full-frame mode (1024 \(\times\) 1024 pixels at 3.51 frames per second) and in the lowest gain setting. Even with these settings, we saturated the peak pixel in roughly a third of the exposures. To compensate we selected frames with peak pixel between 8000 and 9000 ADU, where the detector is linear, such that we are using data between approximately the 75th and 25th percentiles.

VisAO and Clio2 are operated simultaneously. The dichroic entrance window of Clio2 transmits light with \(\lambda \gtrsim 1.05\) \(\mu m\) while reflecting shorter wavelengths to the PWFS and VisAO camera. When working in the thermal IR with Clio2, we perform small pointing offsets (called “nods”) to facilitate background subtraction. These nods occur at intervals ranging from \(\approx2\) to \(\approx5\) minutes depending on wavelength and star brightness. The consequence for VisAO observations is occasionally short (5–15 s) periods of unusable data while the AO loop is paused during a nod. Pausing the loop causes wavefront error (WFE) to become much worse. To automatically reject these periods during postprocessing we apply a WFE cut using AO telemetry (Males et al. 2012). For all of these observations we used a 130 nm rms phase. For the point-spread function (PSF) measurement this rejected 84 frames. We then registered and median-combined the remaining 491 images, with the result shown in Figure 1.

The unsaturated unocculted PSF core has a FWHM of 4.73 pixels (37 mas), compared to the 6.5 m diffraction limit at \(Y_5\) of 3.87 pixels (31 mas). We have identified two sources of broadening: \(\sim7\) mas of residual jitter, most likely due to 60 Hz primary mirror cell fans, and the CCD charge diffusion pixel response function (PRF). For a near- Nyquist sampled CCD, charge diffusion causes a blurring effect, which was well documented for the HST Advanced Camera for Surveys (ACS) and WFPC cameras. See Krist (2003), Anderson & King (2006), and the ACS handbook.\(^{11}\) We measured the PRF in the lab and found that it broadens our PSF by \(\sim0.4\) pixels and lowers the peak such that SR due to PRF alone is 80%. The SR was measured using WFS telemetry, and the unsaturated PSF was 32 \(\pm\) 2%. Because this includes PRF, we can divide by 0.8 to estimate that the true \(Y_5\) SR was 40%.

#### 3.1.2. High-contrast Observations

The observations intended to detect \(\beta\) Pic b were conducted in full-frame mode (1024 \(\times\) 1024 pixels, 8'' \(\times\) 8''), in the camera’s highest sensitivity gain setting, with an individual exposure time of 2.27 s. The star was behind the occulting mask, so no dithers were conducted. The individual images were bias- and

| \(Y_5\)+no mask: | \(Y_5\)+mask: |
|---|---|
| Plate-scale | 7.896 mas pix\(^{-1}\) | 7.874 mas pix\(^{-1}\) |
| Measurement Uncertainty | 0.004 mas pix\(^{-1}\) | 0.005 mas pix\(^{-1}\) |
| Astrometric Uncertainty | 0.019 mas pix\(^{-1}\) | 0.019 mas pix\(^{-1}\) |
| Total Uncertainty | 0.019 mas pix\(^{-1}\) | 0.020 mas pix\(^{-1}\) |

**Notes.** Measurement uncertainty includes both Clio2 and VisAO scatter. Astrometric uncertainty was propagated from the LBT AO/Pisces measurements of Close et al. (2012b).
dark-subtracted, using shutter-closed darks taken at 15 minute intervals throughout the observation. We did not flat field. The CCD-47 has very low pixel-to-pixel variation, and with an 8″ × 8″ FOV we expect only small illumination changes across an image. Clio2 nods were rejected using WFE telemetry as described above. We then examined each image by eye, rejecting those with apparent poor mask alignment or poor AO correction. Finally, to reduce the number of images to process, we median coadded the remaining 3399 dark-subtracted exposures until either 30 s had elapsed or 0.5 of rotation had occurred. This process resulted in 317 images corresponding to 2.5 hr of open-shutter data, with an elapsed clock-time of 4.17 hr and 116° of sky rotation from start to finish. Airmass was 1.12 at the beginning, reached 1.08 at transit, and was at a maximum of 1.29 at the end of the observations.

The coadded images were first coarsely registered and centered using a beam splitter ghost. The mask is partially transmissive (ND ∼ 2.8) in the core. To more finely register the images we located the center of rotational symmetry of the attenuated star using cross correlation with a tolerance of 0.05 pixels. We median-combined the registered images, forming our master PSF. This is shown in Figure 1.

We employed a reduction technique based on principal component analysis, using the Karhunen-Loève Image Processing (KLIP) algorithm of Soummer et al. (2012) (see also Amara & Quanz 2012). We applied KLIP in search regions, as suggested by Soummer et al. (2012), dividing the image in both radius and azimuth in “optimization regions” using the strategy developed by Lafrenière et al. (2007) for the locally optimized combination of images (LOCI) algorithm. In each optimization region we conducted the complete KLIP procedure. Only a subsection of the optimization region, a “subtraction region,” was kept. We used the parameters specifying the regions given by Lafrenière et al. (2007), except that instead of having the same azimuthal width, our subtraction regions were one-third the width of the optimization regions in azimuth. This provided a noticeable (∼10%) improvement in signal-to-noise ratio (S/N) without significantly increasing the computational burden. The final image is formed by combining the individually reduced subtraction regions. Note that when we choose the number of KL modes, we apply this choice to all subtraction regions.

We compare the results of our KLIP reduction to the simultaneously obtained Clio2 H band image, shown in Figure 2 and described in Paper II. The Clio2 position is shown in both images as an ellipse corresponding to the 2σ uncertainty. Here we use the mean position and error using data taken with Clio2 in four filters on subsequent nights. See Paper II for further details.

In Figure 3, we zoom in on the VisAO image of β Pic b and compare it to the PSF at that position under the occulting mask. This under-the-mask PSF was measured on-sky in closed loop by scanning a star across the mask. The mask radically elongates a point source, and the image produced by our KLIP analysis matches this expectation. We also show two representative fake planets, injected using the same PSF (the details of this procedure are given below). The signal recovered at the precisely known location of the planet closely matches the expected signal based on our PSF model.

Other tests conducted included a basic ADI-only reduction, which yields a lower significance detection (S/N ∼ 3). We also tried many other search region geometries. Though varying reduction parameters modulates various speckles throughout the image and changes algorithm throughput, the signal at the location of β Pic b is always detected. We also tested reducing half the data in alternating chunks (to preserve rotation), and even with ADI-only we detected β Pic b using only half the data (albeit with much lower S/N). Along with our PSF comparisons, these results give confidence that our detection of β Pic b is valid. We quantify the significance of this detection next.

### 3.1.3. Detection Significance

To assess the statistical significance of the VisAO detection, we next calculated an S/N map. For this analysis we used 150 KL modes (we discuss choosing the number of modes in Section 3.1.4). The final image was Gaussian smoothed with a kernel of width 3 pixels. Each pixel was divided by the standard deviation calculated in an annulus 1 pixel in width. Pixels within 1 FWHM radius of the location of the planet were excluded from
the standard deviation calculation. The S/N map is shown on the left in Figure 4. Within the 2σ uncertainty of the Clio2 detection β Pic b is detected by VisAO with S/N = 4.1. Other choices of smoothing kernels, different numbers of modes, and different techniques for calculating the noise can change this value by ±25% (see Figure 5). Regardless, this is the maximum S/N pixel at or near the separation of β Pic b, so these choices have minimal impact on the following analysis.

As a starting point we first calculated the histogram of all pixels within the annulus of width ±2σ (Clio2 uncertainty) centered on the location of the planet, excluding the planet location. We restrict ourselves to this annulus to ensure that the statistics are representative. The histogram is shown in Figure 4, where we also overplot a Gaussian distribution with σ = 1 for comparison. There are 2628 pixels included in the histogram, all with S/N < 4.1. We note that these pixels will tend to be correlated across the PSF width and by the smoothing kernel, so we do not estimate a false alarm probability (FAP) from the histogram of individual pixels. However, this does show that the S/N = 4.1 peak at the location of β Pic b is not expected from the distribution of pixels in the image.

In truth, we would have considered any signal close to the location determined by Clio2 as a VisAO detection. We next analyze the 101 unique apertures with a radius of 2σ (Clio2 radial uncertainty) that fit in the same annulus, choosing the highest S/N pixel in each. These apertures have a diameter of ∼7 VisAO pixels, larger than the 4.7 pixel FWHM, so they are uncorrelated with respect to both the PSF and the smoothing kernel. The histogram for these trials is shown at lower right in Figure 4. The probability of having the aperture with the highest S/N pixel occur at the Clio2 position by chance is 1/102 = 1.0% (adding one aperture at the location of the planet). This then sets an empirical upper limit on FAP.

**3.1.4. Photometry with Simulated Planets**

We calibrated our photometry by injecting simulated planets. We used our on-sky under-the-mask PSF measurement, shown in Figure 3 (see also Appendix B) to simulate a planet, which we scaled based on the under-the-mask image of the star in each frame, using a 3 pixel radius photometric aperture. Note that this accounts for Strehl variation and airmass effects. The mask transmission was also applied, taking into account the changing position of β Pic A under the mask over the course of the observation due to flexure and realignment. This caused the transmission at the location of β Pic b to change by roughly ±3%. With this procedure we injected planets with contrasts of 1, 2, and 3 × 10⁻⁵ at 21 locations 13:5 apart in the 270° opposite the location of β Pic b, at the same 59 pixel (∼0.47) separation. This was done prior to registration, and then the complete reduction was carried out, meaning an entirely new set of KL modes was calculated in each search region.

We conducted aperture photometry on these simulated planets and on β Pic b. Using a reduction with no injected planets but otherwise having the same parameters, we estimated the noise in our photometry by sampling 59 locations spaced by 2 FWHM, at the same separation, avoiding the known location of β Pic b. Using a simple grid search strategy, we tested various aperture sizes and Gaussian smoothing kernels. Using the mean photometry of the simulated planets we found the aperture radius and smoothing width that maximized S/N. These values vary depending on the number of modes and contrast. We used the values determined for the 2 × 10⁻³ planets for photometry on the actual β Pic b.

In Figure 5, we show S/N versus number of KL modes for the mean of the simulated 1 × 10⁻⁵ and 2 × 10⁻⁵ planets. In each case, the mean S/N has become nearly constant once 75 modes are included in the reduction. We also show the individual results for each of the 21 injected 2 × 10⁻⁵ planets and the result for β Pic b. The S/N versus number of modes curve for β Pic b varies significantly up to 200 modes, but we see that this appears rather typical compared to the individual injected planets. Combined with the comparisons shown in Figure 3, it appears that our injected fake planets model the true signal well.

In the right-hand panel of Figure 5 we show the contrast of β Pic b. This was calibrated using the injected planets. We linearly interpolated between the mean values of the injected planet photometry, finding the contrast that corresponds to the photometry of β Pic b. The problem we face, illustrated in
Figure 3. Comparison between our image of β Pic b, the occulting mask PSF, and two representative simulated planets that were injected into the data using the mask PSF. The mask PSF was measured on-sky by scanning a star across the mask, and the image at the lower left corresponds to the separation of β Pic b. At lower right, we zoom in on the VisAO detection of β Pic b. As in Figure 2, the red ellipse corresponds to the 2σ Clio2 position uncertainty. The recovered image of β Pic b matches the PSF. The top two images are of simulated planets, injected with contrast $2 \times 10^{-5}$ and recovered using the same data processing pipeline. These show that our injected planets are correctly modeling the PSF. Each image is plotted on the same spatial scale, and the color table is stretched relative to the peak of the object in each as in Figure 2.

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

Figure 5, is that there is no clear choice for number of KL modes. Increasing the number of modes from 75 to 200 does not improve the mean S/N of the injected planets, but it does have a large (~30%) impact on the measured contrast of β Pic b. Rather than choose a single number of modes, we instead average the contrast measurements from 75 to 200 modes. This gives a contrast of $(1.63 \pm 0.49) \times 10^{-5}$. We have adopted an uncertainty of ±30%. Though this is larger than the ~25% expected from the S/N found in Section 3.1.3, it accounts for the additional uncertainty in choosing the number of KL modes. We added the uncertainty in mask transmission (+5%, −10%) in quadrature, so our total uncertainty in contrast is +32%, −30%. In magnitudes we have $\Delta Y_S = 11.97^{+0.34}_{-0.33}$.

3.1.5. VisAO Astrometry

We also used the simulated planets to calibrate our astrometric precision, finding that Gaussian centroiding on the injected planets gave unbiased results. We measured the positions of the $1 \times 10^{-5}$ and $2 \times 10^{-5}$ planets by Gaussian centroiding and used these to estimate the statistical uncertainties. We found $\sigma_{sep} = 0.82$ pixels and $\sigma_{PA} = 0.63$ for β Pic b. In tests using binary stars under the occulting mask, we found a ~1 pixel scatter in recovered positions (at the separation of β Pic b), which we attribute to uncertainty in centroiding under the mask. Finally, we include the astrometric calibration uncertainty (see Table 1). We also measured the position of β Pic b using Gaussian centroiding. Our astrometry for β Pic b is presented in Table 2.

3.2. NICI

We present observations of β Pic b taken during the course of the Gemini NICI (Chun et al. 2008) campaign (Liu et al. 2010b; Wahhaj et al. 2013b; Biller et al. 2013; Nielsen et al. 2013). We observed β Pic on 2010 December 25 UT, in $K_S$, and again on 2011 October 20 UT in $C H_{45.1}$ and $K_{cont}$. The $K_S$ data was independently analyzed by Boccaletti et al. (2013) but with an
Figure 4. Left: S/N map. The white circle shows the 2σ uncertainty in the Clio2 position. We detect β Pic b with VisAO at S/N = 4.1 at the location of the Clio2 detection. Right: pixel S/N histograms. The top panel shows all pixels within the annulus of width ±2σ (Clio2 uncertainty) around the detection. The red curve is the standard normal distribution (not fit to the data), which we show for comparison. The arrow shows the detection of β Pic b. The bottom panel shows the distribution of the maximum S/N in apertures with radius of twice the Clio2 position uncertainty (±2σ). We estimate a conservative upper limit on false alarm probability of FAP = 1.0%.

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

Figure 5. Left: S/N vs. number of KL modes. The thick black curve is the mean of 21 fake planets injected with contrast $2 \times 10^{-5}$. The thick dashed black curve is the same for $1 \times 10^{-5}$ fake planets. The red curve is for β Pic b. Also shown are the results for each of the 21 $2 \times 10^{-5}$ injected planets, showing that the β Pic b result is typical. Right: the resulting contrast measurements. Given that the mean S/N of the fake planets has flattened at 75 modes, we have no clear way to choose how many modes to use. As a result, we average the six contrast measurements from 75 to 200 modes. We adopt an uncertainty of 30%. Though this is larger than implied by our detection S/N = 4.1, it accounts for the additional uncertainty from choosing reduction parameters. The resulting raw contrast measurement is $(1.63 \pm 0.49) \times 10^{-5}$, indicated by the horizontal lines.

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

extrapolated calibration of mask transmission, and hence large photometric uncertainties. Here we provide photometry based on a direct measurement of the focal plane mask transmission. We reduced the NICI data using the well-tested tools developed for the NICI campaign (see references above), with some differences as noted next. The VisAO reduction techniques described above were developed independently.

The images were reduced as described in Wahhaj et al. (2013a) but with the addition of smart frame selection for PSF building similar to Marois et al. (2006) and Lafrenière et al. (2007). The standard ADI reduction procedure median combines all of the science images in the pupil-aligned orientations to make a sourceless PSF and thereby subtract the star from each individual image. In our method, we median-combine only the frames that are similar to the image that is to undergo PSF subtraction. This similarity is measured in the difference of the target image and the candidate reference image using the RMS of pixel values at radii between 0.3 and 0.6 separation. Only the
best 20 images are used to make the reference PSF. We differ from Lafrenière et al. (2007) and Marois et al. (2006) in that we do not reject frames because they have too little rotation relative to the target image. Instead, we require that the range of reference frames selected have total rotation > 2 times the NICI FWHM. These parameters were optimized by comparing the S/N maps resulting from the reductions, and we found that this algorithm performed better than either basic ADI or LOCI for data taken with NICI.

The NICI detections of β Pic b are presented in Figure 6. To estimate the S/N of these detections, each pixel was divided by the standard deviation of the pixels in an annulus of width 5 pixels centered on the same separation. No smoothing was applied. A robust standard deviation algorithm was used, so the much higher pixels at the location of the planet were not included in the estimated noise. The peak S/N in CH4S,1% was 10.4, in KS it was 6.8, and in the K_cont filter it was 27.6.

NICI photometry was calibrated by injecting simulated planets. The simulated planet signals were scaled from the star PSF and were injected into the data at the same separation as the real planet. The star was nonlinear in the CH4S,1% and K_cont science exposures, so we instead used short-acquisition exposures appropriately scaled. The simulated planets were injected into the data at 20 position angles opposite the planet, one at a time, and a complete reduction was carried out. The stellar PSF halo was occasionally saturated near the radius of the planet in the KS observations, and such frames were removed from the reduction process.

We used aperture photometry with an aperture radius of 3 pixels. ADI self-subtraction was corrected using the difference between the injected and recovered flux of the simulated planets. We estimated the uncertainty in the measured flux as the standard deviation of the recovered fluxes. For CH4S,1% and K_cont we estimated an additional uncertainty of 8% due to variability of the star peak.

These observations were made using a 0.′22 radius coronagraphic focal plane mask. The 0.′22 mask opacity falls to zero at 0.′4 from the center of the mask, so we have to correct for the mask opacity at the location of β Pic b. As described in Wahhaj et al. (2011) for the 0.′32 mask, we measured the 0.′22 mask opacities using a pair of Two Micron Sky Survey (2MASS) stars, both off the mask, and then one under the mask at different separations from the center. The mask opacities in the KS, K_cont, and CH4S,1% bands were 5.03 ± 0.03, 5.05 ± 0.03, and 5.47 ± 0.09 mag, respectively. Typically, more than five measurements were taken at each position of the target under the mask, so our opacity measurement uncertainties should be well-estimated (see Wahhaj et al. 2011). The sampling of separations are sparse (in steps of 0.′1), and any discontinuities could introduce systematics into our estimates, which are based on fitting a smooth curve through the opacities as a function of separation. However, we have no evidence that such discontinuities exist, and the uncertainties are estimated with this assumption.

Contrasts were calculated as −2.5 log(star counts/planet counts)+mask opacity. The uncertainties described above were added in quadrature. We measured contrasts of ΔCH4S,1% = 9.65 ± 0.14 mag, ΔKS = 8.92 ± 0.13 mag, and ΔK_cont = 8.23 ± 0.14 mag.

3.3. The SED of β Pictoris A

We used archival photometry of β Pictoris A to find its brightness in the filters used here and also to investigate whether there is any reddening, which could affect our λ < 1 μm photometry. We used V, R_C, and I_C photometry from Cousins (1980b) and Cousins (1980a). Especially useful was photometry in the 13 color system, which spans 0.33 μm to 1.10 μm.

Table 2

| Date         | Filter | Separation (′) | Separation (AU) | P.A. (deg) | Notes                  |
|--------------|--------|----------------|-----------------|------------|------------------------|
| VisAO        |        |                |                 |            |                        |
| 2012 Dec 4   | Y_S    | 0.470 ± 0.010  | 9.14 ± 0.20     | 211.95 ± 1.19 |                        |
| Clio2        |        |                |                 |            |                        |
| 2012 Dec 4/2012 Apr 7 | (mean) | 0.461 ± 0.014  | 8.96 ± 0.27     | 211.9 ± 1.2 | Mean of [3.1], [3.3], L′, and M′ from Paper II |

Notes.

^ Using a distance of 19.44 ± 0.05 pc from van Leeuwen (2007).
^ Clio2 observations, provided here for comparison.

Figure 6. NICI images of β Pic b. The color scale is given on the right, relative to the peak of the planet in each image. The KS image is from 2010 December 25.

(A color version of this figure is available in the online journal.)
in somewhat narrow passbands, from Mitchell & Johnson (1969) and Johnson & Mitchell (1975). In the infrared, we used Johnson–Glass $J$, $H$, and $K$ from Glass (1974), and ESO broadband $J$, $H$, and $K$ and narrow-band $H_0$, $Br_γ$, $K_0$, and CO photometry from van der Bliek et al. (1996). Finally, following Bonnefoy et al. (2013), we synthesize a A6V spectrum by averaging the A5V and A7V spectra in the Pickles Spectral Atlas (Pickles 1998). We then normalized this spectrum to Cousins $V$. We compare this spectrum to the photometry in Figure 7. Based on the good agreement we conclude that reddening is not significant for $β$ Pic A, and we assume that this will also be true for the planet (though there could be circumplanetary reddening that this analysis would miss). This exercise also demonstrates that variability of the primary star is not a concern when using it as a photometric reference for AO observations.

The central wavelength of the 99 filter of Mitchell & Johnson (1969) is nearly identical to VisAO $Y_5$, so we adopt their measurement of $Y_5 = 3.561 \pm 0.035$ mag for $β$ Pic A. Using the interpolated A6V spectrum we find that $CH_{A51%} - H_{\text{ESO}} = 0.024 \pm 0.05$, so we have $CH_{A51%} = 3.526 \pm 0.05$ mag for $β$ Pic A (Bonnefoy et al. 2013). We find $K_{S,\text{NICI}} - K_{E\text{SO}} = -0.026 \pm 0.05$, so we use $K_{S,\text{NICI}} = 3.468 \pm 0.05$ mag. We find $K_{\text{cont}} - K_{\text{ESO}} = 0.068 \pm 0.05$ mag for a A6V, so for $β$ Pic A we have $K_{\text{cont}} = 3.563 \pm 0.05$ mag. We combine these with our contrast measurements, adding uncertainties in quadrature. We present our new photometry of $β$ Pic b in Table 3, along with prior measurements in $J$, $H$, and $K$. Measurements at longer wavelengths are considered in Paper II.

4. ANALYSIS

We now analyze the combined $Y_5$, $J$, $H$, and $K_S$ photometry of $β$ Pic b. Our analysis is based on a library of over 500 field BDs, low-g BDs, and low-mass companions, which we describe in Appendix A.

4.1. Color–Color and Color–Magnitude Comparisons

In Figure 8, we compare $β$ Pic b to field BDs and other low-mass companions in color-color plots. We show $J - K_S$ versus $H - K_S$ colors, where nearly all of the companions have photometry (HR 8799 e is the notable exception in $J$).

![Figure 7. SED of $β$ Pic A. The synthetic spectrum was normalized to the $V$ photometry only. We assume that the lack of reddening also holds for the planet. Also note the lack of significant variability implied by these different measurements. (A color version of this figure is available in the online journal.)](#)

Table 3

| Filter | Instrument | Date    | Apparent Magnitude | Absolute Magnitude | Notes |
|--------|------------|---------|--------------------|--------------------|-------|
| Y5     | VisAO      | 2012 Dec 4 | 15.53$^{+0.34}_{-0.33}$ | 14.09$^{+0.34}_{-0.33}$ | 1     |
| J      | NACO       | 2011 Dec 16 | 14.0 $\pm$ 0.3 | 12.6 $\pm$ 0.3 | 2     |
|        |            | $\ldots$ | 14.11 $\pm$ 0.21 | 12.68 $\pm$ 0.21 | 3     |
| CH_{A51%} | NICI       | 2011 Oct 20 | 13.18 $\pm$ 0.15 | 11.74 $\pm$ 0.15 | 1     |
| H      | NACO       | 2012 Jan 11 | 13.5 $\pm$ 0.2 | 12.0 $\pm$ 0.2 | 2     |
|        |            | $\ldots$ | 13.32 $\pm$ 0.14 | 11.89 $\pm$ 0.14 | 3     |
|        | NICI       | 2013 Jan 9 | 13.25 $\pm$ 0.18 | 11.82 $\pm$ 0.18 | 3     |
| KS     | NACO       | 2010 Apr 10 | 12.6 $\pm$ 0.1 | 11.2 $\pm$ 0.1 | 4     |
|        | NICI       | 2010 Dec 25 | 12.39 $\pm$ 0.14 | 10.94 $\pm$ 0.14 | 1     |
|        | NICI       | 2013 Jan 9 | 12.47 $\pm$ 0.13 | 11.04 $\pm$ 0.13 | 3     |
| K_{cont} | NICI     | 2011 Oct 20 | 11.79 $\pm$ 0.15 | 10.34 $\pm$ 0.15 | 1     |

Notes. (1) this work; (2) Bonnefoy et al. 2014; (3) Currie et al. 2013; (4) Bonnefoy et al. 2011.

The $Y$ band is relatively unexplored territory for low-mass companions, so we present three different permutations of $Y_5$ colors. The field objects are plotted in the NICI system using synthetic photometry as described in Appendix A. We found that conversions between photometric systems are typically <0.1 mag, especially for spectral type L (see also Stephens & Leggett 2004), so in Figure 8 the companion objects are plotted in the $J$, $H$, and $K_S$ photometric system in which they were observed. We used available spectra to estimate $Y_5$ photometry for the companions shown. For $β$ Pic b we plot our new $K_S$ point from NICI and the NICI $H$ point from Currie et al. (2013). In all cases $β$ Pic b has colors consistent with early- to mid-L dwarfs. It is also consistent with an early-T, a consequence of the blueward progression at the L/T transition.

The color degeneracy of the L/T transition is broken by absolute magnitude. In Figure 9, we show $Y_5$ and $K_S$ color–magnitude diagrams. These plots firmly place $β$ Pic b in the early-L dwarfs. As noted by Bonnefoy et al. (2013) and Currie et al. (2013) it is somewhat redder than the L dwarfs in $K_5$ versus $H - K_5$. This is consistent with other low surface-gravity L dwarfs such as AB Pic B, 2M0122B, and PSO318.5, though within 1σ $β$ Pic b is consistent with the field.

4.2. Spectral Fitting

We next fit each of 499 BD spectra collected from various sources to the $Y_5$ through $K_{cont}$ photometry of $β$ Pic b (treating each measurement independently). We did this by computing the flux of each spectrum in each of the bandpasses then finding the single scaling factor that minimized $\chi^2$. Only spectra with a complete $Y$-band measurement were used, which tends to select for high S/N. We adopted an error of 0.05 mag for our synthetic photometry in each bandpass based on the findings of Liu et al. (2013b). This was added in quadrature to the $β$ Pic b measurement errors. The results are presented in Figure 10, where we show $\chi^2$ versus SpT for each of the field objects as well as the median in each SpT. The error bars indicate the standard deviation in each SpT. There is a minimum in the early- to mid-L dwarfs, giving a range of L2–L5.

In Figure 11, we show the five best-fitting spectra, which range from L3 to L5.5. Our new $Y_5$ photometry is well fit by
Figure 8. (a): $J - K_S$ vs. $H - K_S$ colors of $\beta$ Pic b compared to field BDs, low-g BDs, and companions. (b)–(d): various permutations in color–color space including $Y_J$ photometry. We see that $\beta$ Pic b has colors very similar to L0–L5 field dwarfs, though within the $1\sigma$ uncertainties it is consistent with an early-T dwarf. These diagrams emphasize the diversity of low-mass, low-temperature companions. In (d), we see that $\beta$ Pic b is separated from HR 8799 b and 2M1207 b by two magnitudes in $Y_J - K_S$ color, and 2M1207 b is separated from the coolest Y dwarfs by nearly five magnitudes. (A color version of this figure is available in the online journal.)

these spectra, and our new $CH_{4S,1\%}$ and $K_S$ points are consistent with the prior measurements. The $K_{cont}$ point is only consistent with prior measurements at the $2\sigma$ level, though. A possible culprit is the noted nonlinearity of the star, which may have biased the result. However, the same procedure was applied to the $CH_{4S,1\%}$ measurement from the same night. Based on the many measurements of $\beta$ Pic A we discount the primary as a source of variability at this level. BDs are known to be variable (e.g., Buenzli et al. 2012) but typically with low amplitude for early-L dwarfs (Goldman et al. 2008). We do not have enough evidence to speculate other than to note variability in $\beta$ Pic b as a possible explanation.

Though it established that the $Y$ through $K$ photometry of $\beta$ Pic b does not appear to be atypical compared to the field, this exercise ultimately does not yield a well-determined SpT.

4.3. Near-IR SpT

Having established that the photometry of $\beta$ Pic b places it in the early- to mid-L dwarfs, we next attempt to estimate its SpT. Spectral typing is usually done by comparing the spectral morphology of the object to spectral standards. Because there is not yet a measurement of the $Y$ through $K$ spectrum of $\beta$ Pic b, we instead compare its broadband photometry to field objects. We first plot color versus SpT for the 499 spectra in our library, shown in Figure 12. For each color we fit a polynomial to the sequence and then find the root(s) of this polynomial corresponding to the photometry of $\beta$ Pic b. A consequence of the L/T transition is that the BD SpT sequence is dual-valued in each permutation of the $Y_JHK$ colors, hence the double values in most of the panels of Figure 12 (and the broad minimum in Figure 10). The $H - K_S$ color measurements do not intersect the polynomial, though they are consistent with field dwarfs. For these $H - K_S$ measurements we assign the SpT of the turnover in color versus SpT.

The bluer colors of $\beta$ Pic b (e.g., $YS - J$, $J - H$) indicate an SpT of early-L or mid-T. The redder colors especially $H - K_S$ favor mid-L. To break the degeneracy from colors we turn to absolute magnitudes. In similar fashion, we fit polynomials to the objects in our library with parallaxes. These fits, shown on the right in
Figure 9. Color–magnitude diagrams. In the left-hand panel of each plot, we show absolute magnitude vs. color. $\beta$ Pic b falls on or near the early-L dwarf locus. Though it is somewhat red in $H - K_S$ it is 1$\sigma$ consistent with the field. In the right-hand panels, we show the same data organized by SpT. We plot $\beta$ Pic b with an SpT of L2.5$\pm$1.5 based on our analysis of its colors and absolute magnitudes. The HR 8799 EGPs and 2M1207 b are plotted with SpTs of L7.25 based on their locations in the color–magnitude plots.

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

Figure 12, are single-valued and all favor an SpT of early-L. This paints a picture of $\beta$ Pic b as having the luminosity of an early-L dwarf but being somewhat redder than typical for the field, much like many well-studied low-gravity field BDs and companions.

We next compared all of these SpT determinations. It has been shown that low-g BDs do not follow the field BD sequence in near-IR absolute magnitudes (Faherty et al. 2013; Liu et al. 2013a), so we must be cautious about using the absolute magnitudes of $\beta$ Pic b to directly estimate SpT. However, according to Liu et al. (2013a) in the SpT range of roughly L0–L3 the absolute $J$-band magnitudes of low-g objects do match the field. We also note that for spectral types later than L3, the absolute $J$-band magnitudes tend to be fainter than the field for low-g objects, which does not appear to be true for $\beta$ Pic b. The absolute magnitudes of $\beta$ Pic b all correspond to the early-L dwarf SpTs, and the weighted mean using just the absolute magnitudes is L2.1$\pm$0.8. Turning to the colors next, we reject the T classifications based on the absolute photometry. We form a best estimate of SpT by averaging all of the L values, finding 3.6$\pm$2.2 using only the colors, as expected from the range we derived from using Figure 10.

Based on the consistency and the findings of Liu et al. (2013a), we give somewhat more weight to the type estimate derived from absolute magnitudes than the color-derived estimate. We also take into account that low-g objects tend to be red compared to the field for their spectral types. Based on all of these considerations, we adopt L2.5$\pm$1.5 as the near-IR spectral
type of β Pic b. This is consistent with Quanz et al. (2010), who found an approximate spectral type of L4, with a range of L2–L5 given by Currie et al. (2013). We first convert to the MKO photometric system, using the relationships we derive in Appendix A. We then determined the BC for each of J, H, and K using the polynomials given in Liu et al. (2010a). We then took the uncertainty-weighted mean value for each bandpass. The results are presented in Table 4. From there, we determined the temperature, mass, and radius by linear interpolation on the hot-start evolutionary models (Chabrier et al. 2000; Baraffe et al. 2003). We adopt the lithium depletion boundary age of 21 ± 4 Myr for the β Pic moving group from Binks & Jeffries (2013). We treated our estimate for log(Lbol) and this age estimate as Gaussian distributions and drew 10^3 trial values. For each random pair of log(Lbol) and age we calculated the hot-start model prediction for mass, temperature, and radius by linear interpolation on the model grid. The resulting distributions are shown in Figure 13 and summarized in Table 5. The mass distribution has mean and standard deviation 11.9 ± 0.7 M_Jup and median 12.0 M_Jup. The mass distribution has negative skewness, and there appears to be an upper limit at M ≈ 13 M_Jup. For radius we find T_{eff} = 1, 643 ± 32 K. For radius we find R = 1.43 ± 0.02 R_Jup.
with a small positive skewness. These very small uncertainties are the formal errors from our Monte Carlo analysis of the model grid, and they do not include any additional terms such as the uncertainties in the models themselves.

Repeating the Monte Carlo experiment with the prior age estimate of 12 ± 4 Myr from Zuckerman et al. (2001), we found $M = 10.5 \pm 1.5 \ M_{\text{Jup}}$, $T_{\text{eff}} = 1623 \pm 38$ K, and $R = 1.47 \pm 0.04 \ R_{\text{Jup}}$. To account for the asymmetric uncertainty we used the skew-normal distribution for age, choosing its parameters such that the mode was 12 Myr, the left-half width was 4 Myr, and the right-half width was 8 Myr. The resulting 12 Myr distributions are also shown in Figs. 13 and 6. There is again an upper limit on mass at roughly 13 $M_{\text{Jup}}$. We surmise that this is due to our luminosity estimate being too faint to allow deuterium burning at these ages according to the models, hence the mass is strongly constrained to be below 13 $M_{\text{Jup}}$ regardless of age. Note that we consider additional models, using the complete 1–5 μm photometry of β Pic b in Paper II.

Bonnefoy et al. (2013) arrive at an estimate $T_{\text{eff}} = 1,700 \pm 100$ K from fitting PHOENIX-based atmosphere models coupled with various cloud models (Chabrier et al. 2000; Allard et al. 2001; Baraffe et al. 2003) and found $R = 1.4 \pm 0.2 \ R_{\text{Jup}}$. Currie et al. (2013) estimated a range of 1575–1650 K using the various cloud plus atmosphere models of Burrows et al. (2006), Madhusudhan et al. (2011), and Currie et al. (2011b) and estimated $R = 1.65 \pm 0.06 \ R_{\text{Jup}}$. Both of these efforts assumed the previous age estimate of 12 ± 4 Myr.

5. DISCUSSION

It has recently become clear that the SpT to $T_{\text{eff}}$ relationship for low-gravity objects is different from the relationship for the field (e.g., Bowler et al. 2013; Liu et al. 2013b). Like other low-g objects, β Pic b appears to be cooler than field BDs with the same SpT. The SpT to $T_{\text{eff}}$ relationship of Stephens et al. (2009) gives an estimate of $T_{\text{eff}} = 1904 \ K$ for an L2.5 field BD,
which is \( \sim 250 \) K hotter than we calculated assuming hot-start evolution for this young object.

It was noted by Liu et al. (2013b) that low-\( g \) objects tend to have \( L_{\text{bol}} \) consistent with the field for their SpT, despite their lower temperatures and red near-IR colors. In Figure 14, we show \( \log(L_{\text{bol}}/L_\odot) \) versus SpT for field BDs and low-\( g \) BDs and companions. The field BDs are plotted using BCs from Liu et al. (2010a), and companions are plotted using published values of \( L_{\text{bol}} \) (see Table 10 for references). Attempts have been made to use spectral indices and morphology to assign SpTs or make to use spectral indices and morphology to assign SpTs or

Figure 13. Results of Monte Carlo experiments using our luminosity estimate, \( \log(L_{\text{bol}}/L_\odot) = -3.86 \pm 0.04 \), a \( \beta \) Pic moving group age of \( 21 \pm 4 \text{ Myr} \) (solid line) and \( 12^{+9}_{-5} \text{ Myr} \) (dashed line), and hot-start evolutionary models (Chabrier et al. 2000; Baraffe et al. 2003). Note the negative skewness in mass. We can place an upper limit at \( M \approx 13 M_{\text{Jup}} \).

Figure 14. Bolometric luminosity vs. SpT. We expect a temperature sequence to produce a luminosity sequence under the assumption of nearly constant radius. The young low-gravity BDs and EGPs also appear to fall on the same luminosity sequence, as the field BDs despite their lower effective temperatures. The HR 8799 planets and 2M1207 b, objects that do not fit in the standard L spectral types, are plotted as L7.25.

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

6. CONCLUSIONS

We have presented the first high-contrast far-red optical observations of an EGP with MagAO’s VisAO CCD camera, detecting \( \beta \) Pic b in \( Y_{\text{S}} \) at a contrast of \( (1.63 \pm 0.49) \times 10^{-5} \) at a separation of \( 0.470 \pm 0.010 \). The VisAO detection has \( S/N = 4.1 \) and a conservative upper limit on FAP of 1.0%. We also present observations of \( \beta \) Pic b in the near-IR made with the NICI instrument at the Gemini South Telescope. Combining our VisAO \( Y_{\text{S}} \) and NICI \( CH_{\text{ASG}}1.5 \), \( K_{\text{S}} \), and \( K_{\text{cont}} \) photometry with previous measurements in \( J, H \), and \( K \), we estimated that \( \beta \) Pic b has a spectral type of L2.5 \( \pm 1.5 \). In color–color and color–magnitude plots, \( \beta \) Pic b fits very well with other early-L dwarfs, perhaps being slightly redder in \( H-K \).

We used our spectral type estimate to evaluate the physical properties of \( \beta \) Pic b. Using field BD bolometric corrections, we estimate \( \log(L/L_\odot) = -3.86 \pm 0.04 \) dex. This is consistent with previous estimates. Using hot-start evolutionary models at an age of \( 21 \pm 4 \text{ Myr} \), our \( L_{\text{bol}} \) measurement yields a mass estimate of \( M = 11.9 \pm 0.7 M_{\text{Jup}} \), with an upper limit at \( M \approx 13 M_{\text{Jup}} \) due to the model treatment of deuterium burning. For temperature we find \( T_{\text{eff}} = 1, 643 \pm 32 \text{ K} \). For radius we find \( R = 1.43 \pm 0.02 R_{\text{Jup}} \). All of these results are consistent with those of prior studies.

If we instead used the field BD sequence to estimate temperature, we would find a \( T_{\text{eff}} \sim 250 \text{ K} \) hotter than expected from the evolutionary models. The population of low surface gravity ultracool dwarfs and directly imaged EGPs likewise have low effective temperatures compared to field BDs of similar spectral
type. However, these objects tend to be very red in near-IR colors and so do not follow the field BD sequence in color–magnitude diagrams. In contrast to other directly imaged young EGPs (such as HR 8799 b and 2M 1207 b), β Pic b looks much more like a typical early-L dwarf in the near-IR, both in terms of its colors and luminosity, despite its inferred low gravity and cooler temperature.

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A.1. Filters

We obtained a transmission profile and atmospheric transmission profile appropriate for each site. Table 6 summarizes the atmosphere assumptions and models used. We converted to photon-weighted “relative spectral response” (RSR) curves, using the following equation (Bessell 2000):

$$T(\lambda) = \frac{1}{h c} \lambda T_0(\lambda),$$

where $T_0$ is the raw energy-weighted profile. We calculate the central wavelength as

$$\lambda_0 = \int_{0}^{\infty} \frac{\lambda T(\lambda)d\lambda}{\int_{0}^{\infty} T(\lambda)d\lambda}.$$  

We calculate the effective width $\Delta \lambda$, such that

$$F_{\lambda}(\lambda_0)\Delta \lambda = \int_{0}^{\infty} F_{\lambda}(\lambda)T(\lambda)d\lambda.$$  

To calculate the magnitude of some object with a spectrum given by $F_{\lambda, obs}$ we used

$$m = -2.5 \log \left[ \frac{\int_{0}^{\infty} R(\lambda)F_{\lambda, obs}d\lambda}{\int_{0}^{\infty} R(\lambda)F_{\lambda, veg}d\lambda} \right]$$

using the Vega spectrum of Bohlin (2007), which has an uncertainty of 1.5%. These calculations are summarized in Table 7. We next describe details particular to the different photometric systems.

**The Y Band.** The $Y$ band was first defined in Hillenbrand et al. (2002). We follow Liu et al. (2012) and assume that the UKIDSS $Y$ filter defines the MKO system passband because the largest number of published observations in this passband are from there (see Burningham et al. 2013). This is a slightly narrow version of the filter. The UKIDSS Y RSR curve is provided in Hewett et al. (2006), which is already photonormalized and includes an atmosphere appropriate for Mauna Kea.

We also consider the unfortunately named Z filter used at Subaru/IRCS and Keck/NIRC2, which is actually in the $Y$ window rather than in the traditionally optical $Z$/$\zeta$ band. To add to the confusion the filter has been labeled with a lowercase $z$, but the scanned filter curves and Alan Tokunaga’s Web site indicate that it was meant to be capital Z. In any case, it is a narrow version of the $Y$ passband. Here we follow Liu et al. (2012) and refer to it as $z_{1.1}$ to emphasize its location in the $Y$ window and that it is not related to the optical bandpasses of the

**APPENDIX A**

**SYNTHETIC PHOTOMETRY AND CONVERSIONS**

In this Appendix, we provide details of our synthetic photometry. The primary purpose of this is to verify the methodology used for our analysis, but we also determine transformations between various filter systems used in BD and exoplanet imaging that may be useful to others.

12 http://obswww.unige.ch/gcpd/
13 http://ponto.ucsd.edu/~adam/browndwarfs/spexprism
14 https://www.cfa.harvard.edu/~tdupuy/plx/Database_of_Ultracool_Parallaxes.html
15 http://www.ifa.hawaii.edu/~tokunaga/MKO-NIR_filter_set.html
between measurements. The AM has almost no effect on this change in transmission has little impact on differential NICI K
2012). The mean transmission changes by the ATRAN models we assessed the impact of changes in both MKO
YS absorption. We finally determine the photon-weighted RSR. We communication), so this will slightly underestimate atmospheric
Magellan site at Cerro Manqui, the MKO system (see below). We used the same atmospheric assumptions as for the observations reported here, we ignore this effect.

The 2MASS System. The 2MASS J, H, and K<sub>s</sub> transmission and RSR profiles were collected from the 2MASS Web site. The RSR profiles are from Cohen et al. (2003). They used an atmosphere based on the PLEXUS model for AM 1.0. This model does not use a parameterization corresponding directly to PWV, but according to the Web site it is equivalent to 5.0 mm of PWV.

The MKO System. We used the Mauna Kea filter profiles provided by the IRTF/NSCam Web site for the MKO J, H, K<sub>s</sub>, and K passbands that correspond to the 1998 production run of these filters. We again used the ATRAN model atmosphere from Gemini Observatory, now for Mauna Kea with 1.6 mm precipitable water vapor (PWV) at AM 1.0.

The NACO System. We obtained transmission profiles for NACO from the instrument Web site. We used the “Paranal-like” atmosphere provided by ESO, which is for AM 1.0 and 2.3 mm of PWV. The NACO filters are close to the 2MASS system, but there are subtle differences, which are somewhat more pronounced once the atmosphere appropriate for each site is included.

The NICI System. Profiles for the NICI filters were obtained from the instrument Web sites for NICI and NIRI. The Cerro Pachon ATRAN atmosphere was used, with AM 1.0 and 2.3 mm of PWV. The NICI J, H, and K<sub>s</sub> bandpasses are intended to be in the MKO system and so should be insensitive to atmospheric conditions, but there are subtle differences between the filter profiles.

A.2. Photometric Conversions

To quantify the differences between these systems and to accurately compare results for objects measured in the different systems, we used the library of BD spectra we compiled from various sources (described in Appendix A.3). We calculated the magnitudes in each of the various filters and then fit a fourth- or fifth-order polynomial to the results. Our notation is

\[ m_1 - m_2 = c_0 + c_1 \text{SpT} + c_2 \text{SpT}^2 + c_3 \text{SpT}^3 + c_4 \text{SpT}^4 + c_5 \text{SpT}^5. \] (A1)

where SpT is the near-IR spectral type given by

- SpT = 0...9, for M0...M9
- SpT = 10...19, for L0...L9
- SpT = 20...29, for T0...T9.

We provide the coefficients determined in this manner for a variety of transformations in Table 8.

As a check on our calculations, consider the conversions from 2MASS to MKO. There are many objects with measurements in both systems, which allows us to directly compare our synthetic photometry to actual measurements. We here use the compilation of Dupuy & Liu (2012). This also allows a comparison to the previous work of Stephens & Leggett (2004), who employed a methodology similar to ours but with fewer objects. The results are shown graphically in Figure 16. In all

Table 7
Synthetic Photometric System Characteristics

| Filter       | λ<sub>0</sub> (μm) | Δλ (μm) | 0 mag F<sub>0</sub> (10<sup>-6</sup> erg s<sup>-1</sup> cm<sup>-2</sup> μm<sup>-1</sup>) |
|--------------|-------------------|--------|---------------------------------|
| Y Band       |                   |        |                                 |
| PAN-STARRS Y<sub>Y</sub> | 0.9633           | 0.0615 | 7.17                            |
| VisAO Y<sub>Y</sub>  | 0.9847           | 0.0855 | 6.75                            |
| MKO Y        | 1.032            | 0.101  | 5.82                            |
| IRC5 z<sub>Y</sub> | 1.039            | 0.049  | 5.73                            |
| J Band       |                   |        |                                 |
| 2MASS J      | 1.241            | 0.163  | 3.14                            |
| MKO J        | 1.249            | 0.145  | 3.03                            |
| NACO J       | 1.256            | 0.192  | 3.02                            |
| H Band       |                   |        |                                 |
| NICI CH<sub>H</sub>S<sub>Y</sub> | 1.584            | 0.0167 | 1.28                            |
| MKO H        | 1.634            | 0.277  | 1.19                            |
| 2MASS H      | 1.651            | 0.251  | 1.14                            |
| NACO H       | 1.656            | 0.308  | 1.14                            |
| NICI H       | 1.658            | 0.27   | 1.15                            |
| K Band       |                   |        |                                 |
| MKO K<sub>Y</sub> | 2.156            | 0.272  | 0.438                           |
| NACO K<sub>Y</sub> | 2.16             | 0.323  | 0.438                           |
| 2MASS K<sub>Y</sub> | 2.166            | 0.262  | 0.431                           |
| NACO K<sub>S</sub> | 2.176            | 0.268  | 0.424                           |
| MKO K        | 2.206            | 0.293  | 0.403                           |
| NICI K<sub>cont</sub> | 2.272            | 0.0375 | 0.356                           |

same name. We used the same atmospheric assumptions as for the MKO system (see below).

Vis AO Y<sub>S</sub>. The Vis AO Y-short (Y<sub>S</sub>) filter is defined by a Melles-Griot long wavepass filter (LPF-950), which passes λ ≥ 0.95 μm, and the quantum efficiency (QE) limit of our near-IR coated EEV CCD47-20 detector. We convolved the transmission curve with the QE for our EEV CCD47-20 (both provided by the respective manufacturers) and included the effects of three Al reflections. We also include the Clio2 entrance window dichroic that reflects visible light to the WFS and VisAO, cutting on at 1.05 μm. We next multiply the profile by a model of atmospheric transmission, using the 2.3 mm of precipitable water vapor (PWV), airmass (AM) 1.0 ATRAN model for Cerro Pachon provided by Gemini Observatory.(Lord 1992). Cerro Pachon, ~2700 m, is slightly higher than the Magellan site at Cerro Manquí, ~2380 m (D. Osip 2013, private communication), so this will slightly underestimate atmospheric absorption. We finally determine the photon-weighted RSR. We refer to this filter as “Y-short” or Y<sub>S</sub>. This is similar to the Y<sub>Y</sub> bandpass of the PAN-STARRS optical survey (Tonry et al. 2012). Y<sub>S</sub> is ~22nm redder than y<sub>Y</sub>, and we prefer to emphasize that we are working in the Y atmospheric window. Y-band filter profiles are compared in Figure 15.

The Y<sub>S</sub> filter is slightly affected by telluric water vapor. Using the ATRAN models we assessed the impact of changes in both AM and PWV. The mean transmission changes by ±3% over the ranges 1.0 ≤ AM ≤ 1.5 and 2.3 ≤ PWV ≤ 10.0 mm. This change in transmission has little impact on differential photometry so long as PWV does not change significantly between measurements. The AM has almost no effect on λ<sub>0</sub>, but changes in PWV do change it by 2 to 4 nm as expected given the H<sub>2</sub>O absorption band at ~0.94 μm. This is relatively small, and because we have no contemporaneous PWV measurements for the observations reported here, we ignore this effect.

16 http://www.gemini.edu/?q=node/10789

17 http://www.ipac.caltech.edu/2mass/releases/allsky/doc/sec6_4a.html
18 http://irftpweb.ifa.hawaii.edu/~msfcan/filters.html
19 http://www.eso.org/sci/facilities/paranal/instruments/naco/instr/filters.html
20 http://www.eso.org/sci/facilities/paranal/instruments/2mass/filters.html
21 http://www.gemini.edu/sciops/instruments/nici/
22 http://www.gemini.edu/sciops/instruments/niri/
three bands, our synthetic photometry and fit appear to be a good match to the measurements. In J our results appear to be an improvement over Stephens & Leggett (2004), and in $H$ and $K$ either fit appears to be reasonable. These results give confidence that our synthetic photometry reproduces the variations in these systems reasonably well.

A.3. Comparison Objects

$Y_S - K_S$ Spectral Library. We analyzed the $Y_S$JHK$_S$ photometry of $\beta$ Pic b by comparison with a library consisting of 499 BD spectra. Of these, 441 are from the SpeX Prism Spectral libraries maintained by Adam Burgasser (from various sources), 23 are WISE BDs from Kirkpatrick et al. (2011), and 35 are young field BDs from Allers & Liu (2013). We correlated 115 of these with parallax measurements, either listed in the SpeX Library (from various sources) or from Dupuy & Liu (2012). We conducted synthetic photometry on these spectra as described above. For the objects with parallaxes we normalized the spectra to available photometry. In most cases, there is a near-IR SpT assigned that we use here. In the few cases where there is no near-IR SpT, we use the optical SpT.

We also compiled very late-T and early-Y dwarf photometry from Liu et al. (2012) and Leggett et al. (2013). Here we lack spectra, so instead we use the above transformations from the MKO system determined using our compiled spectra.

$Y$-band Photometry of EGPs. The other young planetary mass companions with $Y$-band photometry are HR 8799 b and 2M 1207 b. Currie et al. (2011b) detected HR 8799 b at 1.04 $\mu$m in the $z_{1.1}$ filter with Subaru/IRCS. Oppenheimer et al. (2013) also have the ability to work in the $Y$ band with Project 1640 and reported low S/N detections of HR 8799 b and HR 8799 c at 1.05 $\mu$m. 2M 1207 b was observed with the HST by Song et al. (2006). To compare our results we must convert these measurements into our $Y_S$ bandpass. The SEDs of these two objects do not correspond to those of field BDs of comparable temperature, so we turn to published best-fit model spectra: for

![Figure 15](http://pono.ucsd.edu/~adam/browndwarfs/spexprism/)

*Figure 15.* Comparison of the VisAO $Y_S$ bandpass with other $Y$-band filters. Top: raw filter profiles. The $Y$ bandpass is from Hillenbrand et al. (2002). The “$z_{1.1}$” bandpass is used at Subaru/IRCS and Keck/NIRC2 (where it is called either “$z$” or “$Z$”). Bottom: the filters after photon-weighting and including models for atmospheric transmission; here, we show the UKIDSS “$Y$” RSR curve from Hewett et al. (2006) and the $y_{p1}$ filter of PAN-STARRS (Tonry et al. 2012).

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

Table 8

| Filters | $c_0$ | $c_1$ | $c_2$ | $c_3$ | $c_4$ | $c_5$ | $\sigma$ (mag) |
|---------|-------|-------|-------|-------|-------|-------|----------------|
| $Y_S - Y_{MKO}$ | 0.00904 | 0.0247 | 0.00411 | -0.000633 | 2.89 $\times 10^{-5}$ | -3.96 $\times 10^{-7}$ | 0.038 |
| $z_{1.1} - z_{MKO}$ | 0.00424 | -0.00911 | 0.000823 | -2.85 $\times 10^{-5}$ | 1.23 $\times 10^{-7}$ | 0.0 | 0.011 |
| $J_{2M} - J_{MKO}$ | -0.0308 | 0.0208 | -0.00165 | 6.4 $\times 10^{-5}$ | -5.83 $\times 10^{-7}$ | 0.0 | 0.012 |
| $J_{NACO} - J_{MKO}$ | -0.0895 | 0.0343 | -0.00331 | 0.000145 | -1.87 $\times 10^{-6}$ | 0.0 | 0.015 |
| $H_{2M} - H_{MKO}$ | 0.00358 | -0.00903 | 0.000435 | -1.14 $\times 10^{-5}$ | 1.82 $\times 10^{-7}$ | 0.0 | 0.008 |
| $H_{NACO} - H_{MKO}$ | -0.0521 | 0.0152 | -0.00182 | 8.61 $\times 10^{-5}$ | -1.25 $\times 10^{-6}$ | 0.0 | 0.011 |
| $N_{H} - N_{MKO}$ | -0.0138 | -0.000532 | -0.000303 | 1.92 $\times 10^{-5}$ | -2.69 $\times 10^{-7}$ | 0.0 | 0.008 |
| $N_{H} - N_{NACO}$ | -0.0383 | 0.0157 | -0.00151 | 6.69 $\times 10^{-5}$ | -9.76 $\times 10^{-7}$ | 0.0 | 0.007 |
| $N_{H} - C_{H15.1}$ | -1.28 | 0.695 | -0.152 | 0.0164 | -9.31 $\times 10^{-4}$ | 0.0 | 0.037 |
| $K_{2M} - K_{MKO}$ | -0.324 | 0.149 | -0.0233 | 0.00171 | -5.91 $\times 10^{-5}$ | 7.54 $\times 10^{-7}$ | 0.014 |
| $K_{2M} - K_{S,MKO}$ | 0.0272 | -0.0155 | 0.00227 | -1.71 $\times 10^{-4}$ | 6.12 $\times 10^{-6}$ | -7.8 $\times 10^{-8}$ | 0.006 |
| $K_{S,NACO} - K_{S,MKO}$ | 0.0428 | -0.0209 | 0.00422 | -3.39 $\times 10^{-4}$ | 1.22 $\times 10^{-5}$ | -1.59 $\times 10^{-7}$ | 0.007 |
| $K_{S,NIC1} - K_{MKO}$ | -0.154 | 0.0828 | -0.0142 | 0.00112 | -4.06 $\times 10^{-5}$ | 5.35 $\times 10^{-7}$ | 0.011 |
| $K_{S,NIC1} - K_{S,NIC1}$ | 0.00554 | 0.000497 | 0.00128 | -1.24 $\times 10^{-4}$ | 4.59 $\times 10^{-6}$ | -6 $\times 10^{-8}$ | 0.007 |
| $K_{S,NIC1} - K_{cont}$ | 1.07 | -0.524 | 0.108 | -0.00999 | 0.000428 | -6.96 $\times 10^{-6}$ | 0.058 |

http://pono.ucsd.edu/~adam/browndwarfs/spexprism/
Figure 16. Synthetic photometry (red points) in the 2MASS and MKO systems and measurements made in the two systems (crosses, from Dupuy & Liu 2012). We also plot the binned median of the measurements. Our polynomial fit is shown as the solid black line. For comparison we show the fit determined by Stephens & Leggett (2004), who also used synthetic photometry. Our fit to the synthetic photometry appears to be a better match to the actual measurements in J. In the H and K bands, both fits appear to be acceptable, with Stephens & Leggett (2004) being somewhat better for M and L dwarfs in H.

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

Figure 17. Optical and near-IR photometry and models of 2M 1207 b and HR 8799 b. To estimate photometry in the Y atmospheric window, we used the models to calculate colors and then extrapolated or interpolated from the measured photometry. Measured photometry is indicated by filled circles, and our estimated photometry is indicated by asterisks. The 2M 1207 b model is from Barman et al. (2011b), and the HR 8799 b model is from Madhusudhan et al. (2011). See also Table 9.

(A color version of this figure is available in the online journal.)
Figure 18. Transmission of the VisAO occulting mask. The dot-dashed line is the median smoothed profile measured in the laboratory (Strehl > 90%). The solid black line is a piecewise polynomial fit to the on-sky scans with 300 modes of wavefront correction. The individual points correspond to measurements of β Pic A and binaries. The red curve is our bootstrapped profile for 200 modes of wavefront correction. The separation of β Pic b is ~59 pixels ≈0.28, which gives a mask transmission of 0.60±0.10.

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

APPENDIX B

VisAO OCCULTING MASK TRANSMISSION

We first measured the mask transmission and PSF by scanning an artificial test source across the mask with the instrument off the telescope. Our internal alignment source has a slightly faster f/#, resulting in smaller FWHM (it was originally designed for the LBT AO systems), and it delivers a Strehl > 90%. The source was scanned along 12 different lines, spaced roughly 30° apart, across the mask in the Y5 filter. We found the center of the mask by determining the x,y position that best symmetrizes all of the scans simultaneously. We measured attenuation of the mask using a 3 pixel radius photometric aperture. The results of our laboratory scans are shown in Figure 18. The maximum attenuation is 0.0015, or ND = 2.8.

During the first-light commissioning run (Comm1, November–December 2012), we observed a 0.28, ΔV ≈ 3.5 binary both on and off the mask, providing a single transmission measurement. The center of the mask was found using AO-off (seeing-limited) acquisition images, which show a well-defined circular shadow. This is also plotted in Figure 18 and is over 200% higher than expected based on the lab scans. The key point is that this measurement was done with a 200 mode reconstructor, with gains applied to only the first 120 modes.

We can also use acquisition images of β Pic A, recorded during coronograph alignment. These sample much closer in than the position of the planet but provide guidance on the
changes in the transmission profile due to wavefront correction. We also include the median transmission of β Pic A centered on the mask, which was measured using the science exposures. During the β Pic observations the same reconstructor was used as for the 0′′28 binary, but gains were applied to all 200 modes. We thus expect slightly better correction.

During our second commissioning run (Comm2, 2013 March–April), we scanned a star across the mask with the AO on the mask, which was measured using the science exposures. We measured this both in the lab and on-sky by fitting an elliptical Gaussian at each point in the scans. The result is shown in Figure 18, is intermediate between the lab and the 0′′28 binary.

In Figure 19, we show the ratio of coronagraph transmission for β Pic A (200 modes), the 0′′28 binary (120 modes), and the 0′′64 binary (300 modes) to the transmission profile measured on-sky (300 modes). To form an estimate of the complete transmission profile under 200 modes of wavefront control, we fit this ratio with a piecewise linear function, which we then multiply by the on-sky profile. Our fit is obviously not the only functional form that could be used to describe the transmission change from 300 to 200 modes of correction, but it is the simplest estimate we can make given the data. We note that even significant changes in the ratio close to the center result in relatively small changes in the transmission at 59 pixels, the even significant changes in the ratio close to the center result in relatively small changes in the transmission at 59 pixels.
Figure 19. Ratio of mask transmission at lower wavefront correction quality to the transmission measured on-sky with 300 modes. The solid line is a piecewise correction function that we use to form a bootstrap estimate of transmission under 200 modes of wavefront correction. This results in the red curve shown in Figure 18.

Figure 20. PSF shape measurements. The broad apodized transmission profile results in a PSF that varies with distance from the coronagraph center. We plot the ratio of FWHMs of the elliptical Gaussian that best fits the PSF at each location. On-sky, the ratio does not reach 1.0 because there is usually an elongation in the wind direction. Correction quality also appears to have an effect on shape because the on-sky measurements have a lower peak FWHM ratio. See also Figure 3.

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

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