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HD 143811 AB b: A Directly Imaged Planet Orbiting a Spectroscopic Binary in Sco-Cen

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ABSTRACT

We present confirmation of HD 143811 AB b, a substellar companion to spectroscopic binary HD 143811 AB through direct imaging with the Gemini Planet Imager (GPI) and Keck NIRC2. HD 143811 AB was observed as a part of the Gemini Planet Imager Exoplanet Survey (GPIS) in 2016 and 2019 and is a member of the Sco-Cen star formation region. The companion object is detected ~ 430 mas from the host star by GPI. With two GPI epochs and one from Keck/NIRC2 in 2022, we confirm through common proper motion analysis that the object is bound to its host star. We derive an orbit with a semi-major axis of 64^{+32}_{-14} au and eccentricity ~ 0.23 . Spectral analysis of the GPI H -band spectrum and NIRC2 L' photometry provides additional proof that this object is a substellar companion. We compare the spectrum of HD 143811 AB b to PHOENIX stellar models and Exo-REM exoplanet atmosphere models and find that Exo-REM models provide the best fits to the data. From the Exo-REM models, we derive an effective temperature of 1042^{+178}_{-132} K for the planet and translate the derived luminosity of the planet to a mass of $5.6 \pm 1.1 M_{\text{Jup}}$ assuming hot-start evolutionary models. HD 143811 AB b is one of only a few planets to be directly imaged around a binary, and future characterization of this object will shed light on the formation of planets around binary star systems.

Keywords: Exoplanets, Direct Imaging, Binary stars, Substellar companion stars, Exoplanet astronomy

1. INTRODUCTION

The direct imaging of exoplanets is a technically demanding endeavor that requires spatially separating the faint light of the planet from its host star. Since the first detections of exoplanets with direct imaging (G. Chauvin et al. 2004; C. Marois et al. 2008; A. M. Lagrange et al. 2009), this technique allows discovery of gas giant planets down to orbital separations of 3 au (e.g., M. Nowak et al. 2020). Some of the successfully imaged planets are a result of targeted searches, where the gravitational influence of the planet was identified from other observations (e.g., M. Nowak et al. 2020). Many others are discovered through blind surveys of young, nearby stars, where direct imaging instruments are most sensitive to planets (e.g., B. Macintosh et al. 2015; G. Chauvin et al. 2017). By imaging these planets over time, we are able to measure their orbital motion, identify gravitationally stable orbits (e.g., J. J. Wang et al. 2018a), and study how they influence smaller bodies in the system (e.g., M. A. Millar-Blanchaer et al. 2015). Additionally, by directly observing the light of the planets, we can spectroscopically study the emission

of their atmosphere in order to measure the temperature (A. Z. Greenbaum et al. 2018), elemental composition (E. Nasedkin et al. 2024), radial velocity, and rotation speeds (I. A. G. Snellen et al. 2014).

Nearly all of the directly imaged planets discovered to date are found orbiting single stars³⁸. One contributing factor for the lack of planets imaged around binaries is that direct imaging surveys generally disfavor binary stars in their target selection strategy (C. Thalmann et al. 2014). There are only a few directly imaged exoplanets known to orbit around an inner binary. HD 106906 b (V. Bailey et al. 2014; L. Rodet et al. 2017), b Cen b (M. Janson et al. 2021), and WISPIT 1bc (R. F. van Capelleveen et al. 2025) are directly imaged planets that orbit at extremely wide separations that make in-situ formation through core accretion unlikely. HD 106906 b is thought to have experienced a series of dynamical interactions that resulted in its final orbit to be > 700 au from the stellar binary, which orbit each other within 1 au (L. Rodet et al. 2017; M. M. Nguyen et al. 2021). It may also have a high planetary obliquity

³⁸ Note that some directly imaged systems such as 51 Eri b orbit a single star but have stellar companions at large separations (B. Macintosh et al. 2015)

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relative to the system’s debris disk, which could be explained by formation through turbulent gravitational instability (M. L. Bryan et al. 2021). For b Cen b, the large projected separation of 550 au combined with a modest eccentricity disfavors strong dynamical interactions and may point to it forming in-situ through gravitational instability (M. Janson et al. 2021). There are also a few planetary-mass companions with masses that straddle the boundary between planets and brown dwarfs that orbit around binaries: Ross 458C (B. Goldman et al. 2010; Z. Zhang et al. 2021), SR 12 C (M. Kuzuhara et al. 2011; Y.-L. Wu et al. 2022), 2MASS J01033563-5515561 (AB)b (P. Delorme et al. 2013), and ROXs 42B b (T. Currie et al. 2014; A. L. Kraus et al. 2014). These four objects orbit low-mass stars and, with the exception of 2MASS J01033563-5515561 (AB)b, definitely orbit beyond 100 au. For ROXs 42B b, these reasons, combined with a solar atmospheric composition, points to formation via gravitational instability (J. W. Xuan et al. 2024).

The Gemini Planet Imager (GPI) was a high-contrast imaging instrument on Gemini South (B. Macintosh et al. 2014). GPI was equipped with a high-order adaptive optics system to correct atmospheric turbulence (L. A. Poyneer et al. 2016), an apodized Lyot coronagraph to suppress the glare of the star (R. Soummer et al. 2011), and an near-infrared integral field spectrograph for imaging exoplanet systems (J. K. Chilcote et al. 2012). The GPI Exoplanet Survey (GPIES) was a 5 year survey of young, nearby stars to search for gas giant planets. GPIES discovered one of the coolest planets imaged to date, 51 Eri b (B. Macintosh et al. 2015), a brown dwarf orbiting within a debris disk (Q. M. Konopacky et al. 2016), and imaged many other debris disks (T. M. Esposito et al. 2020). The first half of GPIES shows that giant planets are relatively rare beyond 10 au and that their occurrence rate is related to host star mass (E. L. Nielsen et al. 2019). A small fraction of the stars observed by GPI were known spectroscopic binaries with inferred angular separations between the host star to be < 20 mas, since these did not affect the high-contrast performance of GPI (E. L. Nielsen et al. 2019). Furthermore, at the time of the survey, HD 143811 AB had not yet been identified as a binary and was therefore included as a target.

In this work, we present the confirmation of a ~ 5 -6 Jupiter mass planet orbiting the spectroscopic binary at HD 143811 AB at ~ 60 au. This work is part of the final companion vetting and data analysis by the GPIES team. We note that the planet was also identified as a candidate in GPI data by an independent analysis that did not have sufficient data to confirm the candidate (V.

Squicciarini et al. 2025). In particular, they report a tentative detection of $\sim 3.5\sigma$ in a follow-up epoch, indicating potential common proper motion. In this paper, Section 2 summarizes the host binary star properties, Section 3 describes the GPI and NIRC2 data used in this analysis, and Section 4 discusses the confirmation of the planet HD 143811 AB b through both astrometric and spectroscopic analysis.

2. HD 143811 AB

HD 143811 AB is a member of the Sco-Cen star formation region (P. T. de Zeeuw et al. 1999). The Sco-Cen subgroup to which it belongs is somewhat uncertain; P. T. de Zeeuw et al. (1999), M. J. Pecaut et al. (2012), and P. A. B. Galli et al. (2018) find it to be a member of Upper Scorpius (US), though K. L. Luhman & T. L. Esplin (2020) does not. The next most likely subgroup is Upper Centaurus-Lupus (UCL) (J. Gagné et al. 2018). We assign an age of 13 ± 4 Myr for HD 143811 AB, from ages of Upper Sco of 10 ± 3 Myr and UCL of $\sim 16 \pm 2$ Myr (M. J. Pecaut & E. E. Mamajek 2016). Such an age range follows the 2D map of Sco-Cen ages of M. J. Pecaut & E. E. Mamajek (2016).

HD 143811 AB is a spectroscopic binary (O. V. Zakhozhay et al. 2022; A. Grandjean et al. 2023), which is characterized in depth in a companion paper (A. E. Peck et al. 2025, submitted ApJL). Based on unresolved photometry and multi-epoch high resolution spectra obtained with FEROS (A. Kaufer et al. 1999), the stellar binary has a period of 18.59098 ± 0.00007 days, and a mass ratio of 0.885 ± 0.003 . From this analysis, we adopt masses of the two components of $M_A = 1.30^{+0.03}_{-0.05} M_\odot$ and $M_B = 1.16^{+0.03}_{-0.04} M_\odot$. With only an SB2 RV orbit we cannot currently constrain the full 3D orbit of the binary, however future orbit monitoring may shed light on the full architecture of this system.

To generate a synthetic spectral energy distribution of the unresolved binary we used the procedure outlined in E. L. Nielsen et al. (2019). A joint evolutionary and atmospheric model was created using a modified version of the MESA Isochrones and Stellar Tracks (MIST) model grid (A. Dotter 2016; J. Choi et al. 2016) and the ATLAS9 atmospheric model spectra (F. Castelli & R. L. Kurucz 2003). An MCMC-based approach was used to sample the posterior distributions of the masses of each component (M_1 , M_2), the age (t) metallicity ($[M/H]$) and parallax (ϖ) of the system, and the visual extinction towards the system (A_V). Gaussian priors on the age (13 ± 4 Myr; synthesizing the age for the US and UCL sub-groups from M. J. Pecaut & E. E. Mamajek 2016), parallax (7.3065 ± 0.0204 mas; Gaia Collaboration et al. 2023), metallicity (-0.05 ± 0.11 dex; E. L.

Nielsen et al. 2013), and mass ratio (0.889 ± 0.004) were used. At each step, the predicted flux of the blended system was compared to the *Gaia* (Gaia Collaboration et al. 2023) and 2MASS (M. F. Skrutskie et al. 2006) photometry. A synthetic spectrum at GPI’s resolution, as well as a synthetic *L*-band flux, was calculated by drawing randomly from the converged chains.

3. OBSERVATIONS AND DATA ANALYSIS

In this paper, we utilize two data sets from the Gemini Planet Imager (GPI) at Gemini South and one data set from NIRC2 at the W. M. Keck Observatory. We provide more details on the observations from both instruments below.

3.1. Gemini/GPI Observations

HR 143811 AB was observed by GPI two times as part of the GPI Exoplanet Survey. Both observations were obtained with the GPI integral field spectrograph (IFS) in *H* band ($1.50 - 1.80 \mu\text{m}$) with a spectral resolution $\Delta\lambda/\lambda \sim 40$. The first epoch was taken on 2016 April 30 (UT) (GS-2015B-Q-500) and consists of 36 good exposures of 60 s. The second epoch was taken on 2019 August 11 (UT) (GS-2019A-Q-500) and consists of 45 good exposures of 60 s.

Initial data reduction for each epoch was done using the automated data reduction system for GPIES (J. J. Wang et al. 2018b). The details are listed in Appendix A of J. J. Wang et al. (2018b), but we will briefly summarize the steps here. Individual raw 2-D data from the IFS were transformed into 3-D spectral data cubes (x, y, λ) using the GPI Data Reduction Pipeline version 1.6.0 (M. D. Perrin et al. 2014, 2016). The GPI Data reduction pipeline also corrects for bad pixels, corrects for distortion (Q. M. Konopacky et al. 2014), and measures the position and flux of the four satellite spots (A. Sivaramakrishnan & B. R. Oppenheimer 2006; C. Marois et al. 2006b) for astrometric and photometric calibration (J. J. Wang et al. 2014). The stellar point spread function (PSF) is subtracted from each data set using pyKLIP (J. J. Wang et al. 2015), a Python implementation of the Karhunen-Loève Image Projection (KLIP) algorithm, using both angular differential imaging (ADI; M. C. Liu 2004; C. Marois et al. 2006a) and spectral differential imaging (SDI; C. Marois et al. 2000). The forward model matched filter (FMMF) planet detection code (J.-B. Ruffio et al. 2017) was then run on each epoch using both a L-type and T-type spectral template. The FMMF flux maps are shown in Figure 1 for each epoch. Using the L-type spectral template, HD 143811 AB b was detected at an signal-to-noise ratio (SNR) of 7.7 in the 2016 epoch and an SNR of 3.5 in the 2019 epoch.

We also utilize pyKLIP to measure the astrometry, obtain the relative flux ratio of the companion, and extract a spectrum. To obtain precise astrometric measurements, we first generate a forward model template of the planet PSF through the PSF subtraction process (C. Marois et al. 2010; A. M. Lagrange et al. 2010) using the KLIP-FM formalism (L. Pueyo 2016; J. J. Wang et al. 2016) and using the known flux ratio between the satellite spots and the star (R. J. De Rosa et al. 2020a). Then, the posterior of the planet’s location obtained using Bayesian parameter estimation using the emcee package (D. Foreman-Mackey et al. 2013) and Gaussian processes to model the spatially correlated noise in the images (J. J. Wang et al. 2016). To convert from pixel locations to relative astrometry, we use a platescale of $14.166 \pm 0.007 \text{ mas/pixel}$ and a North-angle offset of $-0.10 \pm 0.13 \text{ deg}$ (R. J. De Rosa et al. 2020b). The astrometry for both epochs is tabulated in Table 1. Following A. Z. Greenbaum et al. (2018), KLIP-FM is also used to extract an *H*-band spectrum from the 2016 April 30 epoch, because it is the best detection. The error on the extracted spectrum is measured by injecting simulated point sources into the data at the same distance from the star as the real companion, re-extracting the simulated source spectra, and using the standard deviation of the re-extracted spectra across all injected sources as the error in the extracted companion spectrum. Then, we obtain the companion spectrum by normalizing against the stellar SED model described in Section 2. Like other GPI spectra (e.g., A. Rajan et al. 2017), the spectra exhibits a high degree of correlated noise, with the scatter between neighboring data points being much smaller than the calculated uncertainties.

3.2. Keck/NIRC2 Observations

HD 143811 AB was observed on 2022 June 10 (UT) with Keck/NIRC2 in *L'* band ($3.426\text{--}4.126 \mu\text{m}$) using the infrared pyramid wavefront sensor to correct for atmospheric turbulence (C. Z. Bond et al. 2018), but not using a coronagraph. 175 exposures were taken, with each exposure comprising of 60 coadds of 0.5 second integration times and utilizing only a 256-pixel subwindow of the detector. A total of 87.5 minutes of total integration time on target were obtained. Additional shorter exposures comprising of 60 coadds of 0.1 second exposures were taken of the star for flux calibration. The data were taken in vertical angle mode, enabling ADI to be used. We note that there is another epoch of Keck/NIRC2 data in *L'* band taken on 2022 April 29 with the vortex coronagraph. However, the star appears significantly offset from the center of the vortex coronagraph in that epoch, making measurements such

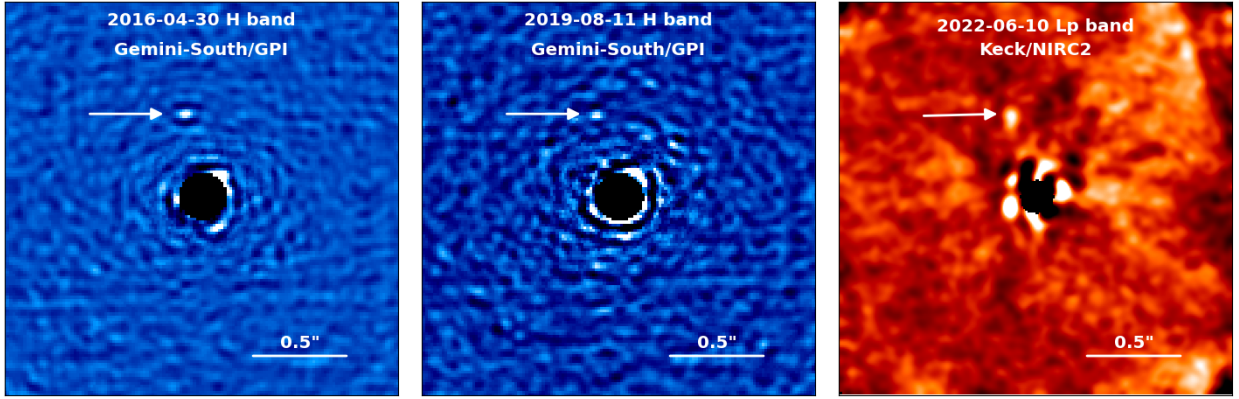


Figure 1. Reduced flux maps of HD 143811 AB obtained by Gemini/GPI in 2016 and 2019 (left and center) and Keck/NIRC2 in 2022 (right). These images are $2'' \times 2''$. North is up and East is left. The star is at the center of the image behind the coronagraph. Arrows indicates the location of the companion. Intensity scales are linear and vary for each image in order to highlight the companion.

Table 1. Observations and Measurements of HD 143811 AB b

Date (UT)	2016 Apr 30	2019 Aug 11	2022 Jun 10
Instrument	GPI	GPI	NIRC2
Filter	<i>H</i>	<i>H</i>	<i>L'</i>
Total Int. Time (min)	36	45	87.5
ρ (mas)	429 ± 3	429 ± 10	421 ± 9
θ (deg)	11.9 ± 1.0	15 ± 3	18.7 ± 1.2
Flux Ratio	$(1.4 \pm 0.3) \times 10^{-5}$	$0.78^{+0.87}_{-0.46} \times 10^{-5}$	$(1.8 \pm 0.8) \times 10^{-4}$
Apparent Magnitude	19.82 ± 0.19	—	16.56 ± 0.32
Absolute Magnitude	14.14 ± 0.19	—	10.87 ± 0.32
Flux ($\text{W}/\text{m}^2/\mu\text{m}$)	$(1.37 \pm 0.24) \times 10^{-17}$	$0.77^{+0.80}_{-0.48} \times 10^{-17}$	$(1.26 \pm 0.36) \times 10^{-17}$

as relative astrometry biased. Thus, we did not include that epoch in our analysis.

We performed initial preprocessing of the data using a general NIRC2 pipeline originally developed for the vortex coronagraph (W. J. Xuan et al. 2018; G. Ruane et al. 2019). First, we corrected bad pixels and flat-field effects in each image. Then, we subtracted the thermal background from the sky and instrument using principal component analysis (PCA), similar to what was done in R. Galicher et al. (2011). Afterwards, the star position in each frame was measured with a 2-D Gaussian fit to each frame. We then performed stellar PSF subtraction using pyKLIP to remove the glare of the star from this preprocessed image sequence. For each science frame, we used all other science frames where the planet would have moved by at least four pixels due to ADI to build the 10 principal components that were used to model the stellar PSF off the glare of the star. The resulting

images are mean combined, and a Gaussian-smoothed image is shown in Figure 1.

To measure the relative astrometry and flux ratio of the companion, we followed a similar procedure to the GPI data. We forward modeled the PSF of the point source through KLIP using the 0.1-second exposures of the star and the KLIP-FM framework, and we performed PSF fitting using Markov-chain Monte Carlo sampling with the emcee package to infer the detector position and flux ratio of the companion following the procedure. To estimate the uncertainty of the companion parameters, we injected simulated of the same brightness and distance from the star into the data at other azimuthal positions, performed the same PSF fitting routine, and used the spread in the measured properties of the simulated planets as the uncertainty in the detector position and flux ratio of the companion. To convert from detector position to relative astrometry, we used the NIRC2 platescale of 9.971 ± 0.004 mas/pixel

and North angle offset of $0.262 \pm 0.020^\circ$ (M. Service et al. 2016), added an additional $0.118 \pm 0.006^\circ$ North angle offset that was found for the pyramid wavefront sensor mode of NIRC2 (Walker et al. submitted), and conservatively assumed a star center uncertainty of 0.5 pixels. We did not apply a distortion correction since the differential distortion across a 500 mas-radius circle centered around the star is smaller than the 0.1-pixel uncertainty on the distortion solution (M. Service et al. 2016). To calculate the L' flux of the companion, we scaled it to the star's L' photometry using the stellar SED model in Section 2. The astrometry and photometry are tabulated in Table 1.

4. PROPERTIES OF HD 143811 AB b

4.1. Companionship and Orbit

We confirm that the close companion is a common proper motion companion using the method described in R. J. De Rosa et al. (2015). *Gaia* DR3 proper motion and parallax are used to predict the motion of a stationary background object, based on the relative astrometry of the companion at the original epoch of detection (see Figure 2). We also use the Orbits for the Impatient (OFTI) algorithm (S. Blunt et al. 2017) to generate plausible orbit tracks from this first epoch, assuming a total system mass of $2.46 M_\odot$. The separation measurements disagree with the background track at $\gtrsim 20\sigma$, and are much more consistent with a mostly-unchanging separation over the timespan of the observations. As a result, we conclude at high confidence that HD 143811 AB b is not a stationary background object.

The relative astrometry is consistent with orbital motion, and we run an OFTI fit on the three epochs of data, assuming a parallax of 7.31 ± 0.02 mas, and a total mass of $2.46 \pm 0.07 M_\odot$. Other priors are taken to be uniform in $\log(a)$, eccentricity, $\cos(i)$, argument of periastron, position angle of nodes, and epoch of periastron passage. We find orbital parameters consistent with a face-on, moderate eccentricity orbit, with semi-major axis, eccentricity, inclination angle, and period of $a = 64_{-14}^{+32}$ au, $e = 0.23_{-0.16}^{+0.24}$ (68% of orbits have $e < 0.34$), $i = 38 \pm 16^\circ$, and $P = 330_{-100}^{+280}$ yr, respectively. To determine if there is any significant dynamical mass constraints, we perform an additional orbit fit that incorporates the differential proper motions from the Hipparcos-Gaia Catalog of Accelerations (T. D. Brandt 2021) assuming all of the detected astrometric acceleration is from the HD 143811 AB b, but we were not able to exclude any companion masses between 1 and $100 M_{\text{Jup}}$.

4.2. Spectral Analysis

We performed spectral comparisons in order to assess and characterize the nature of the object. As discussed in E. L. Nielsen et al. (2017), objects can be ruled out as background stars or cool substellar companions based on the spectrum. A catalogue of reference spectra was assembled using the PHOENIX synthetic stellar model grid (T. O. Husser et al. 2013) and Exo-REM exoplanet atmosphere model grid, which includes both clouds and disequilibrium chemistry in its self-consistent model (B. Charnay et al. 2018). We access the Exo-REM grid using the `species` package (T. Stolker et al. 2020). The final comparison sample is 842 templates from PHOENIX and 9575 from Exo-REM for a range of T_{eff} from 13500 – 400 K. The spectra are blurred to the resolution of GPI using a Gaussian filter.

These data were used in a custom χ^2 goodness of fit routine to determine the best fitting model. We performed the fit for the GPI spectrum alone and, additionally, for the GPI spectrum plus the NIRC2 L' photometry, shown in Figure 3. We do not account for correlated error in the χ^2 analysis. The GPI only fit results in a spread of preferred effective temperatures ($\sim 1100 - 660$ K). While Exo-REM yields slightly lower χ^2 , the PHOENIX grids also fit the data well, with a maximum $\chi^2 \sim 3.4$ (Top panel of Figure 4). However, adding the Keck/NIRC2 data to the spectrum shows that the Exo-REM grid is strongly preferred (Bottom panel of Figure 4). The rejection of PHOENIX stellar templates provides further evidence that our detection is not a background star but rather a substellar companion. The best-fit ($\chi^2 = 3.31$) model parameters of the GPI + Keck fit are effective temperature, $T_{\text{eff}} = 1050$ K, surface gravity, $\log(g) = 4.5$, metallicity $10\times$ solar ($[\text{Fe}/\text{H}] = 1.0$), and C/O ratio equal to 0.35, although we note that $\log(g)$, $[\text{Fe}/\text{H}]$, and C/O ratio are unconstrained as we discuss in the next paragraph. This model is plotted against the candidate spectrum in Figure 3.

For a more precise characterization of the planet's atmospheric properties, we fit the GPI H -band spectrum and NIRC2 L' photometry to the Exo-REM atmospheric models to estimate the range of likely atmospheric parameters. To account for correlated noise in the GPI spectra, we also fit a Gaussian process to model the correlated noise behaviour following the procedure described in J. J. Wang et al. (2020). We sampled the posterior using the nested sampling algorithm (J. Skilling 2004; J. Skilling 2006) with multiple bounding ellipsoids (F. Feroz et al. 2009) from `dynesty` (J. S. Speagle 2020; S. Koposov et al. 2024). The data are sufficient to constrain the effective temperature to 1042_{-132}^{+178} K and the radius to $1.7_{-0.4}^{+0.7} R_{\text{Jup}}$. The

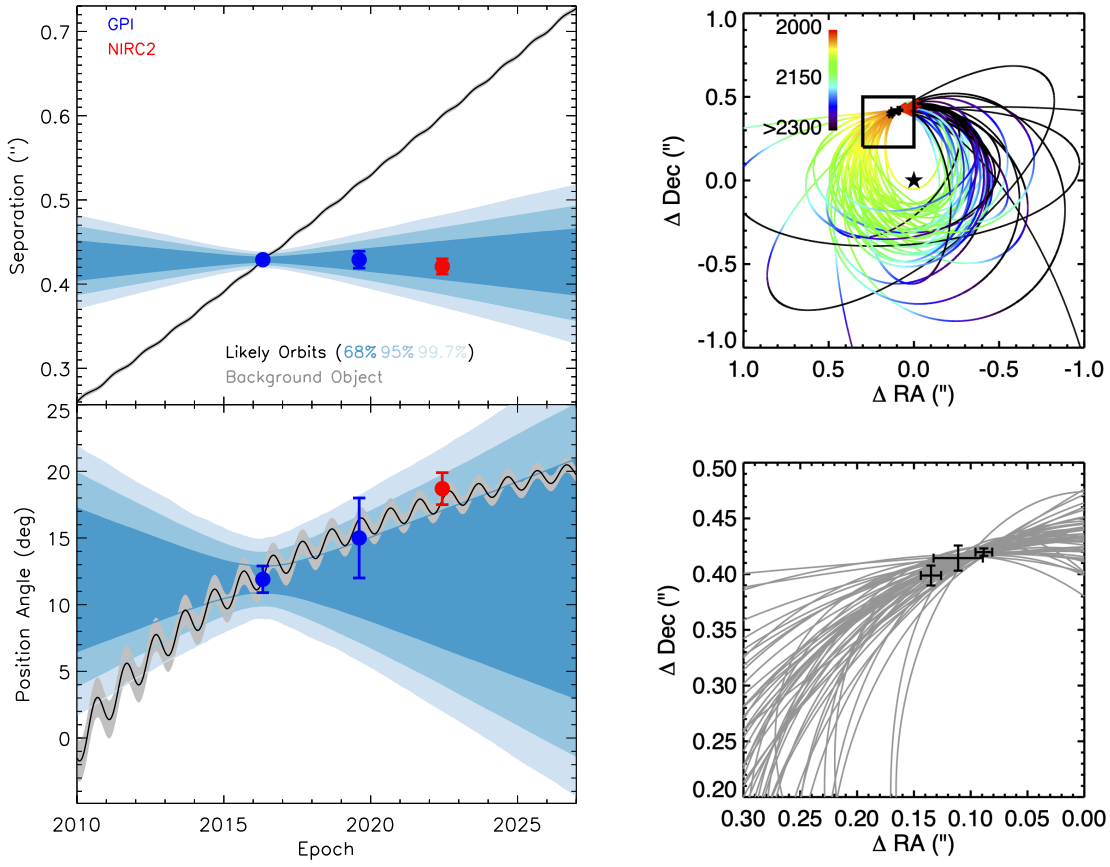


Figure 2. (left) Astrometric measurements for HD 143811 AB b as a function of observational epoch. Points in blue are from GPI and red, Keck NIRC2. The grey lines show the path of a stationary background object, while the blue regions show the paths of possible orbits for a planetary mass bound companion. With these three epochs, HD 143811 AB b is confirmed to be a bound companion at high confidence. (right) Orbit fits are consistent with a mostly-circular orbit with moderate inclination and an orbital period of ~ 300 years.

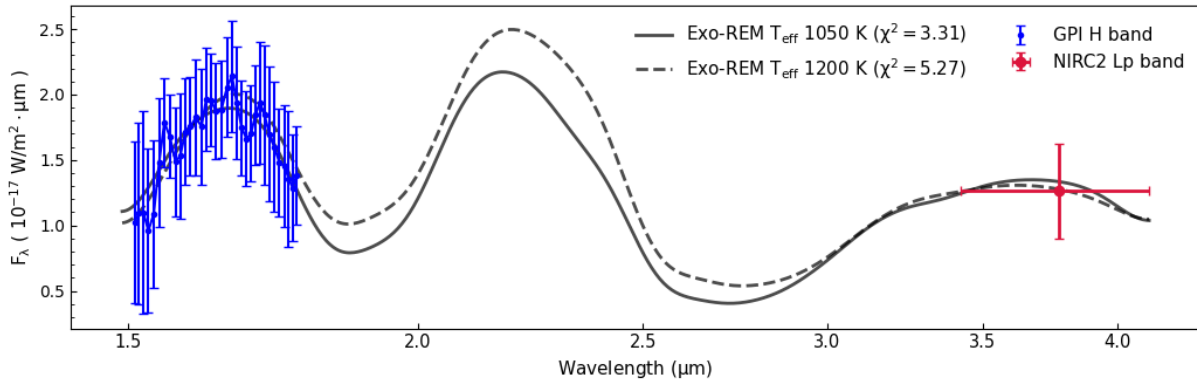


Figure 3. Spectrum of HD 143811 AB b from GPI data (blue, H-band) and Keck (red, L' -band). We also plot the best-fit Exo-REM model (solid gray; $\chi^2 = 3.31$) as well as a second Exo-REM model with a T_{eff} 150 K higher (dashed gray; $\chi^2 = 5.27$).

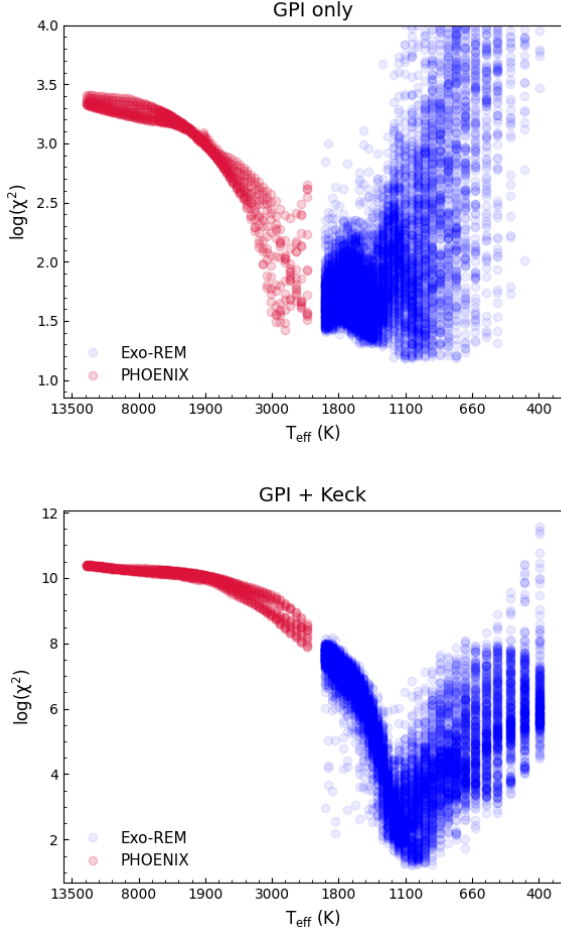


Figure 4. Resulting χ^2_ν as a function of T_{eff} from spectral comparison of HD 143811 AB b with comparison library. Fit values using the PHOENIX stellar models are shown in red, while the Exo-REM comparisons are shown in blue. Note the different y-axes. Both fits prefer the Exo-REM models over PHOENIX, though the addition from Keck focuses the fit to ~ 1100 K.

$\log(g)$, metallicity, and C/O ratio are all unconstrained, with allowed values across the entire parameter space of the model grid. From the constrained effective temperature and radius, we derive a planet luminosity of $3.3^{+0.8}_{-0.6} \times 10^{-5} L_\odot$. Note that effective temperature and radius are negatively correlated in our posteriors, resulting in a luminosity that is more constrained than radius itself. Using the age of the system of 13 ± 4 Myr and hot-start evolutionary models from I. Baraffe et al. (2003), we use our computed luminosity to derive a planet mass of $5.6 \pm 1.1 M_{\text{Jup}}$. We also infer a radius of $1.41 \pm 0.03 R_{\text{Jup}}$ from evolutionary models, consistent with the radius inferred from the Exo-REM fits.

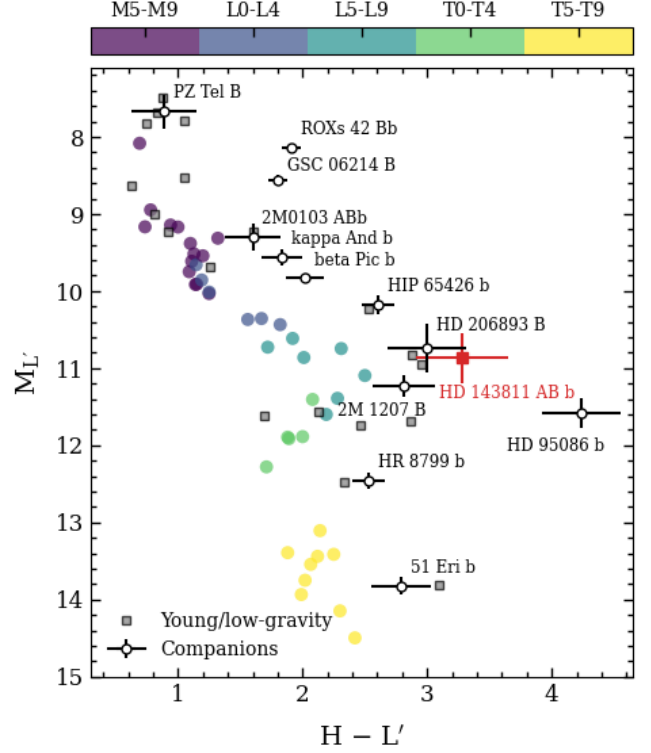


Figure 5. Color magnitude diagram showing HD 143811 AB b (red square) with directly imaged companions, field objects (colored circles), and young/low-gravity objects (squares), which is accessed using `species` (T. Stolker et al. 2020). The color of field objects varies according to spectral type (colorbar above the plot).

4.3. Color-Magnitude Diagram

Further information on the nature of HD 143811 AB b may be gleaned by adding HD 143811 AB b to a color-magnitude diagram with other directly-imaged companions and brown dwarfs. In Figure 5 we show a color-magnitude diagram produced with `species`. Colors and magnitudes of field and low-gravity objects are sourced from the UltracoolSheet (W. M. J. Best et al. 2024) whereas companion properties are included within the `species` package. We calculate H and L' magnitudes for HD 143811 AB b and derive $H_{\text{GPI}} - L'_{\text{NIRC2}} = 3.3 \pm 0.4$, using the 2016 GPI epoch and the NIRC2 data. We do not calculate H magnitude using the 2019 observation since the contrast has large error bars. The absolute magnitude M_L of HD 143811 AB b is consistent with late L-type or early T-type field objects.

Proximity to other directly imaged companions on a CMD may help infer properties such as spectral type. The companion HD 143811 AB b is located on the CMD near two other directly imaged companions, HD 206893 B and 2M 1207 B. HD 206893 B was also im-

aged by GPIES and is one of the reddest planetary-mass companions known. The GPI observations are presented in K. Ward-Duong et al. (2021) along with discussion of a few sources for the dusty red color, with atmospheric dust in the form of high-altitude aerosols as the most viable. They find a spectral type of $L6 \pm 2$ for HD 206893. HD 143811 AB b is also spatially located near 2M 1207 B which has spectral type $L0 \pm 0.5$ (K. L. Luhman et al. 2023). Lastly, the companion is located near another exceptionally red object, HD 95086 b, which is also considered as a Solar System analog. G. Chauvin et al. (2018) find that spectral types L7 – L9 fit their observations of HD 95086 b. Obtaining additional spectra of HD 143811 AB b may reveal a similarly dusty, red nature.

5. CONCLUSIONS

HD 143811 AB b is a substellar companion to a spectroscopic binary in the Sco-Cen star formation region. Our conclusions are summarized below:

- Using the two epochs of GPI data in H band and additional Keck L' data, we rule out the object as a stationary background source using common proper motion.
- Spectral comparisons of the extracted companion spectra to stellar and exoplanet atmosphere models additionally confirms that this object is a physically bound exoplanet companion. Fitting the spectrum of HD 143811 AB b to PHOENIX stellar models yields very large values of χ^2 , while Exo-REM exoplanet atmosphere models fit our data well (best fit $\chi^2 = 3.31$).
- Orbit fitting is performed using OFTI using the three relative astrometry measurements. We find a semi-major axis of $a = 64^{+32}_{-14}$ au and near circular orbit ($e = 0.23^{+0.24}_{-0.16}$).
- We perform spectral fitting of HD 143811 AB b to Exo-REM atmosphere models and derive an effective temperature of 1042^{+178}_{-132} K and a planet luminosity of $3.3^{+0.8}_{-0.6} \times 10^{-5} L_{\odot}$. Using hot-start evolutionary models, we derive a planet mass of $5.6 \pm 1.1 M_{\text{Jup}}$.

Most directly imaged exoplanets have been discovered around single stars, not binaries, making HD 143811 AB b an interesting individual system for follow-up characterization. Follow-up observations that better pinpoint the orbit of both HD 143811 AB b around the binary and the orbit of binary will help unveil the dynamical architecture of this three-body system. HD 143811 AB b will be an interesting test case

to probe atmospheric signatures of planet formation and assess whether this planet in a binary star system is consistent with the predictions of core accretion. This companion object is also part of a larger sample of planets imaged by the GPIES survey. Folding this planet and vetting the remaining candidates from GPIES will help improve our constraints on the frequency of giant planets beyond 10 au orbital separations. Future observations with upgraded direct-imaging instruments, such as the Gemini Planet Imager 2.0 (J. Chilcote et al. (2024); C. Marois et al. (2024)), hopefully can discover even more planets around binaries for characterization.

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This work has made use of data from the European Space Agency (ESA) mission *Gaia* (<https://www.cosmos.esa.int/gaia>), processed by the Gaia Data Processing and Analysis Consortium (DPAC, <https://www.cosmos.esa.int/web/gaia/dpac/consortium>). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the *Gaia* Multilateral Agreement.

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Software: GPI Data Reduction Pipeline (M. D. Perrin et al. 2014, 2016), `pyKLIP` (J. J. Wang et al. 2015), `VIP` (C. A. Gomez Gonzalez et al. 2017; V. Christiaens et al. 2023), `emcee` (D. Foreman-Mackey et al. 2013), `dynesty` (J. S. Speagle 2020; S. Koposov et al. 2024), `species` (T. Stalker et al. 2020), `astropy` (Astropy Collaboration et al. 2013, 2018, 2022), `numpy` (C. R. Harris et al. 2020), `matplotlib` (J. D. Hunter 2007)

APPENDIX

A. ORBIT FIT

Included below are plots of orbital motion (Figure A1) and posteriors from OFTI (Figure A2). We also include a table of posteriors and best-fit orbital parameters (Table A1).

B. GPI SPECTRUM

We include a table of the spectrum extracted from the 2016 April 30 GPI observation of HD 143811 AB b (Table B2).

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Table A1. Posteriors and best-fitting orbital parameters of HD 143811 AB b

Parameter	Median	68% CI	95% CI	99.7% CI	Min. χ^2	Max Likelihood
Semi-major Axis (au)	63.881	50.345–96.412	39.354 – 202.632	33.519 – 628.152	50.764	59.547
Eccentricity	0.231	0.069–0.470	0.010 – 0.714	0.001 – 0.892	0.205	0.016
Inclination Angle (deg)	37.543	20.936–53.422	7.999 – 67.826	1.941 – 79.197	3.964	40.225
Argument of Periastron (deg)	179.950	53.202–295.117	8.247 – 351.328	0.519 – 359.478	140.979	263.654
Position Angle of Nodes (deg)	180.230	66.397–311.038	6.428 – 353.251	0.393 – 359.608	18.763	357.092
Epoch of Periastron Passage (yr)	2112.574	2061.066–2287.424	2010.707 – 2932.706	2000.706 – 7383.107	2104.960	2210.992
Period (yr)	326.347	228.138–605.062	157.633 – 1843.184	123.828 – 10034.210	238.791	284.978
Total Mass ($M_\odot$)	2.451	2.381–2.520	2.311 – 2.591	2.241 – 2.660	2.294	2.600

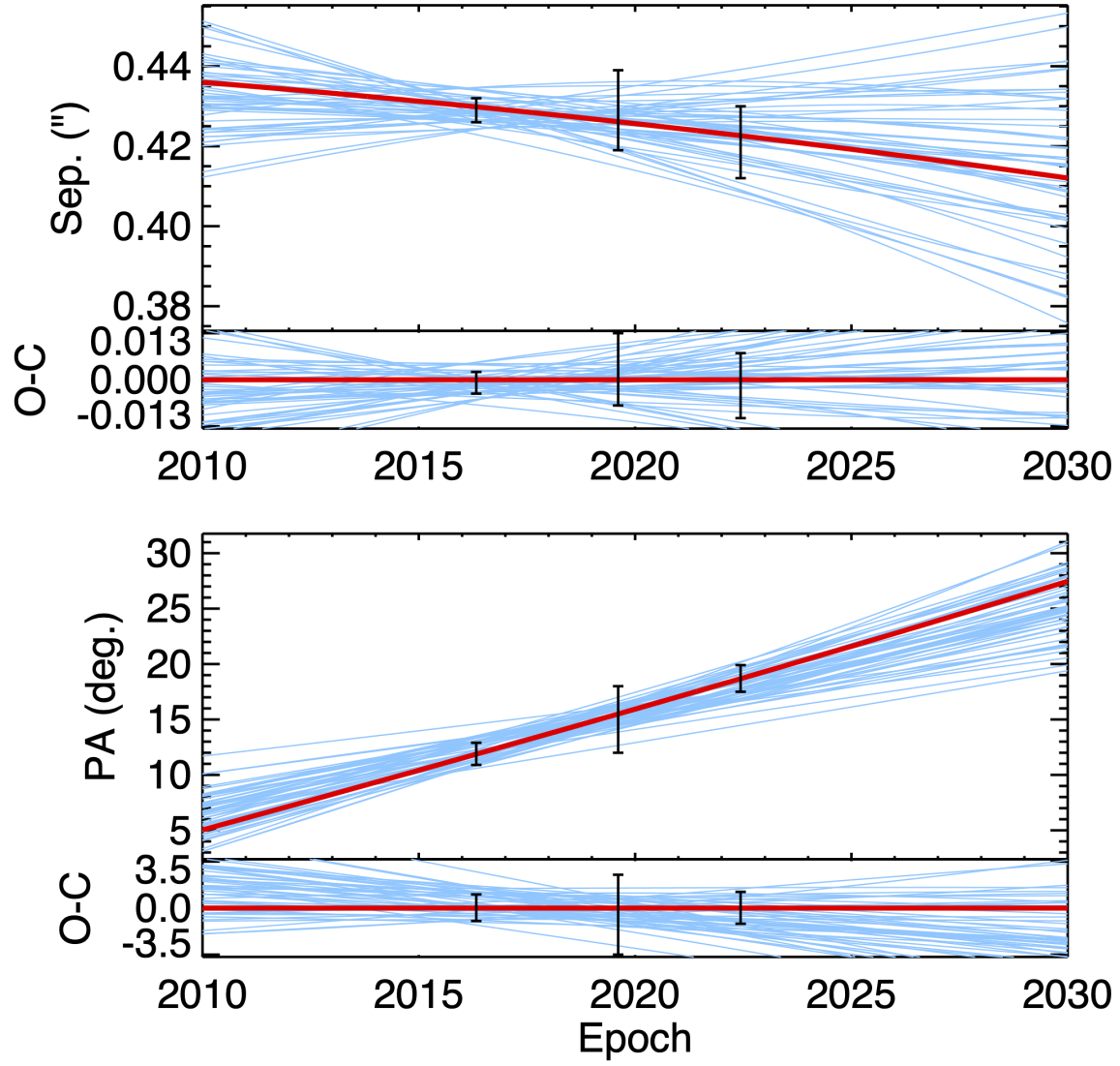


Figure A1. Orbital motion from the OFTI fit to the relative astrometry of HD 143811 AB b. Over the next decade separation is expected to decrease slightly, while position angle increases (counterclockwise motion).

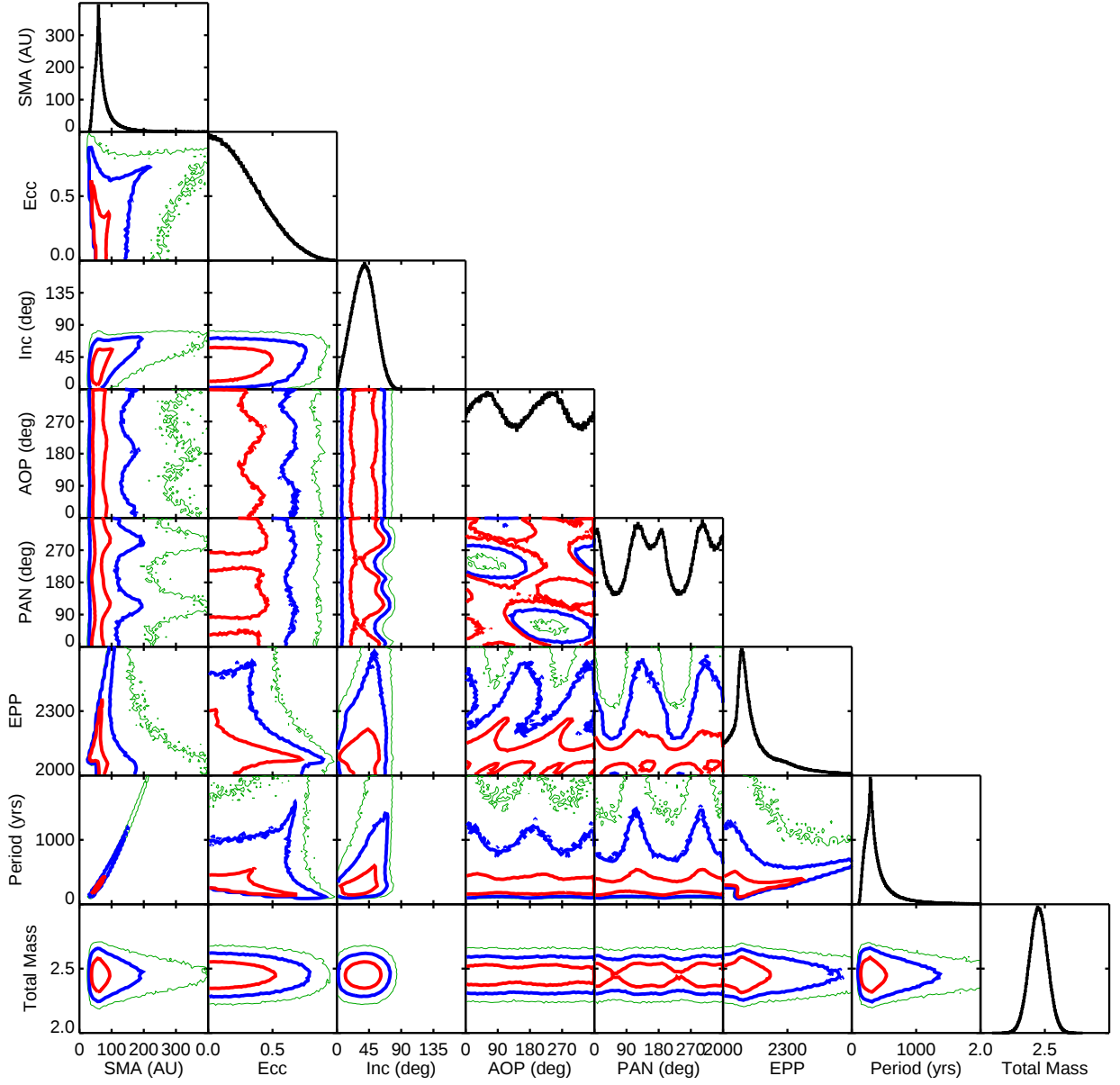


Figure A2. Posteriors from the OFTI orbit fit of HD 143811 AB b, based on three epochs of relative astrometry. Orbits with eccentricity $\lesssim 0.5$ are generally preferred, with semi-major axis of ~ 60 au and period of ~ 300 years.

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Table B2. 2016 GPI Spectrum of HD 143811 AB b

Wavelength (μm)	Flux Ratio	Flux Ratio Error	Flux ($W/m^2/\mu m$)	Flux Error ($W/m^2/\mu m$)
1.510	9.709e-06	4.99e-06	1.028e-17	6.18e-18
1.517	1.085e-05	5.66e-06	1.093e-17	6.94e-18
1.523	1.078e-05	6.40e-06	1.100e-17	7.75e-18
1.531	1.016e-05	5.27e-06	9.600e-18	6.29e-18
1.539	1.126e-05	4.81e-06	1.089e-17	5.65e-18
1.547	1.429e-05	4.26e-06	1.481e-17	4.94e-18
1.555	1.639e-05	3.00e-06	1.787e-17	3.42e-18
1.564	1.576e-05	2.86e-06	1.682e-17	3.20e-18
1.573	1.501e-05	3.80e-06	1.487e-17	4.18e-18
1.580	1.572e-05	4.44e-06	1.531e-17	4.81e-18
1.588	1.747e-05	3.80e-06	1.717e-17	4.06e-18
1.596	1.791e-05	3.56e-06	1.755e-17	3.76e-18
1.605	1.878e-05	4.24e-06	1.826e-17	4.41e-18
1.614	1.865e-05	4.34e-06	1.755e-17	4.43e-18
1.621	1.982e-05	3.89e-06	1.964e-17	3.91e-18
1.629	2.025e-05	3.60e-06	1.957e-17	3.56e-18
1.637	2.038e-05	3.77e-06	1.876e-17	3.66e-18
1.646	2.107e-05	3.88e-06	1.888e-17	3.69e-18
1.655	2.351e-05	4.05e-06	2.058e-17	3.79e-18
1.663	2.438e-05	4.64e-06	2.141e-17	4.27e-18
1.671	2.272e-05	4.77e-06	1.937e-17	4.31e-18
1.679	2.122e-05	4.05e-06	1.745e-17	3.59e-18
1.687	2.123e-05	4.14e-06	1.661e-17	3.62e-18
1.695	2.257e-05	4.22e-06	1.703e-17	3.64e-18
1.702	2.466e-05	4.49e-06	1.845e-17	3.82e-18
1.710	2.635e-05	5.57e-06	1.937e-17	4.68e-18
1.718	2.682e-05	6.47e-06	1.845e-17	5.32e-18
1.726	2.646e-05	6.44e-06	1.699e-17	5.17e-18
1.734	2.605e-05	6.32e-06	1.601e-17	4.97e-18
1.743	2.451e-05	5.33e-06	1.483e-17	4.13e-18
1.752	2.315e-05	6.09e-06	1.451e-17	4.66e-18
1.759	2.203e-05	6.84e-06	1.359e-17	5.19e-18
1.766	2.142e-05	5.46e-06	1.288e-17	4.10e-18
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