Dynamical masses for the nearest brown dwarf binary: ε Indi Ba, Bb

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Abstract. We present preliminary astrometric results for the closest known brown dwarf binary to the Sun: ε Indi Ba, Bb at a distance of 3.626 pc. Via ongoing monitoring of the relative separation of the two brown dwarfs (spectral types T1 and T6) with the VLT NACO near-IR adaptive optics system since June 2004, we obtain a model-independent dynamical total mass for the system of 121 M_Jup, some 60% larger than the one obtained by McCaughrean et al. (2004), implying that the system may be as old as 5 Gyr. We have also been monitoring the absolute astrometric motions of the system using the VLT FORS2 optical imager since August 2005 to determine the individual masses. We predict a periastron passage in early 2010, by which time the system mass will be constrained to < 1 M_Jup and we will be able to determine the individual masses accurately in a dynamical, model-independent manner.

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INTRODUCTION

The brown dwarf binary ε Indi Ba, Bb [1, 2] was discovered through a search for high proper motion sources. It shares a high common proper motion (4.7"/yr) with the K4V star, ε Indi A (HD 209100), at a separation of 1459 AU. ε Indi A has a precise HIPPARCOS distance of 3.626 ± 0.009 pc [3], making these the nearest known brown dwarfs. The binary comprises two T dwarfs with spectral types T1 and T6, and the Lyon models of Baraffe et al. [4] were used to estimate temperatures and masses of 47±10 M_Jup and 28±7 M_Jup for Ba and Bb, respectively, assuming an age of 1.3 Gyr. The age was thought to be relatively well constrained at between 0.8 and 2 Gyr [1], although a significantly older age is favoured by King et al. (2008, in prep; see also [5]) based on new optical/IR photometry and spectroscopy. As a consequence, we are currently pursuing a more accurate age estimation for ε Indi A via asteroseismology.

However, the brown dwarf masses can be determined independently. The separation of the binary at discovery was 0.723", corresponding to 2.65 AU, yielding a nominal orbital period of 16 years assuming the model masses. Thus we have been monitoring...
TABLE 1. System parameters obtained with the preliminary best fit to the relative astrometric data using the code of Gudehus [6].

| Parameter                        | Value       |
|----------------------------------|-------------|
| Period (years)                   | 11.2 ± 0.5  |
| Date of periastron passage       | 2010.1 ± 0.6|
| Eccentricity                     | 0.53 ± 0.03 |
| Inclination (°)                  | -77.2 ± 0.7 |
| Semimajor axis (")               | 0.67 ± 0.03 |
| System mass (M⊙)                 | 0.116 ± 0.001|
| System mass (MJup)               | 121 ± 1     |

the relative separation of the two brown dwarfs using the VLT NACO near-IR adaptive optics system since June 2004 to obtain a model-independent dynamical total mass for the system. We have also been monitoring the absolute astrometric motions of the system using the VLT FORS2 optical imager since August 2005 to determine the individual masses. Fortunately, the system passed apastron shortly after discovery, making it possible to obtain a good preliminary fit to the orbit after only 4 years of observations: periastron is predicted to occur in early 2010, at which point accurate individual masses will be available, thus providing strong constraints on models of these benchmark low-mass objects at an intermediate age.

RELATIVE ASTROMETRY

We have been monitoring the relative orbital motions of ε Indi Ba and Bb with NACO on the VLT in the J, H, and Ks bands since May 2004: here we present a total of 28 epochs obtained up to August 2008 (see Fig. 1). The NACO N90C10 dichroic is used, diverting 90% of ε Indi Ba’s flux to the NACO IR wavefront sensor: the resulting spatial resolution is typically 0.06–0.1" FWHM, meaning simple centroiding can be used to measure separations. The wide (~9") binary system HD 208371/2 is also measured in each band at every epoch to determine the plate-scale and orientation. Images are sky-subtracted and flat-fielded, and positions are measured using standard IRAF packages. Separations and position angles are calculated and errors propagated using a MATLAB script. Relative separations are typically accurate to ±2–3 mas at each epoch, dominated by uncertainties in the relative proper motions of HD 208371/2. Using calibrated position angle and separation data for these 28 epochs, we have obtained a preliminary orbital fit (see Fig. 1) and an estimate of the total dynamical mass of the system using the binary package of Gudehus [6] (see Table 1). Although only ~35% of the orbital period has been covered, the fortunate catching of apastron shortly after discovery already leads to a relatively accurate fit. Further details of the data reduction and analysis and orbit fitting will be given by McCaughrean et al. (2008, in prep).
FIGURE 1. Position of ε Indi Bb relative to Ba over the period May 2004 to August 2008. Blue symbols are the data, with blue crosses showing the errors, while red squares represent the orbital fit prediction. Periastron is predicted to be in ~2010.1.

ABSOLUTE ASTROMETRY

We have also been monitoring the absolute motions of ε Indi Ba and Bb across the sky in the I-band with the VLT FORS2 instrument with data obtained at 33 epochs from May 2005 to May 2008. Given their proximity to the Sun, both brown dwarfs are bright enough to be accurately tracked against a net of faint field stars covering a total field of view of 8.53 × 8.53 arcmin. Images were dark-subtracted, flat-fielded, and sky-subtracted, prior to stellar positions being determined in each image using DAOPHOT. As the FORS2 data are seeing-limited (typically 0.5–0.6” FWHM) and the brown dwarf components only partly resolved, PSF fitting must be used to determine their positions accurately. A PYRAF script is used to match positions between epochs and to determine relative x, y positions throughout. In the field, ~60 stars are used to construct an internal astrometric reference frame and to calculate the relative x, y positions. Of these, 16 have 2MASS positions and are used to make the transformation into α, δ in the FK5 reference frame. The data clearly show the large (4.7”/yr) proper motion of the two sources across the sky, along with a ~0.3” parallax wiggle due to their distance of 3.626 pc (see Fig. 2). However, the 3 years of data taken to date have been near apastron, where the relative orbital motion of ε Indi Ba and Bb has been rather small. While the high acceleration at apastron provides a good preliminary estimate of the total system mass, a larger movement on the sky of Bb relative to Ba is needed to establish the location of the system barycentre and thus determine the mass ratio. This aim should, however, be achieved
FIGURE 2. Absolute motion of the binary across the field from May 2005 to May 2008. The FORS2 data are shown as points while the continuous curves are calculated given the relative orbit as fit from the NACO data, the \( \sim 0.25" \) parallax motion due to the 3.626 pc distance of the source and its position in ecliptic coordinates, the 4.7" arcsec/yr proper motion, and assuming a mass ratio \( Ba:Bb \) of 70:50. \( \varepsilon \) Indi Ba is in blue, Bb in red. There has been insufficient relative orbital motion as yet to unambiguously separate the individual masses.

by late 2010 when the system has passed periastron and the maximum relative orbital motion has been seen.

RESULTS AND FUTURE WORK

The key result identified thus far in our study is that the total system dynamical mass of 121 M\( \text{Jup} \) is \( \sim 60\% \) larger than the 75 M\( \text{Jup} \) derived by McCaughrean et al. [2] based on photometry, spectral types, and evolutionary models. However, the dominant uncertainty in that latter estimate was due to the age of \( \varepsilon \) Indi A, taken to be in the range 0.8–2 Gyr as given by Lachaume et al. [7]. If the system were significantly older, the evolutionary model masses would need to be larger to account for the observed luminosity and thus might be more in line with the directly-measured dynamical masses. Indeed, our detailed spectroscopic analysis of the brown dwarfs [5] suggests that the system may in fact be as old as 5 Gyr, thus potentially removing the mass discrepancy.

Direct dynamical mass determinations for brown dwarfs provide a vital calibration of evolutionary and atmospheric models covering a range of masses, ages, and metallicities.
The first results from such monitoring studies are now becoming available, but due to its proximity to the Earth and association with a well-known and well-characterised star, the $\epsilon$ Indi Ba, Bb binary remains one of the very best suited to such studies. The high quality relative orbit data obtained to date clearly demonstrate that a very precise system mass can be determined: simulations show that with two more years of data including periastron in 2010, the system mass will be constrained to significantly better than $1\,M_{\text{Jup}}$, i.e. $<1\%$. Furthermore, the unique possibility of following the absolute astrometric motions of both sources in wide-field optical imaging means that we will also be able to determine the individual masses accurately in a dynamical, model-independent manner.

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