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VLT/NACO astrometry of the HR 8799 planetary system*

L′-band observations of the three outer planets

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ABSTRACT

Context. HR 8799 is so far the only directly imaged multiple exoplanet system. The orbital configuration would, if better known, provide valuable insight into the formation and dynamical evolution of wide-orbit planetary systems.
Aims. We present data which add to the astrometric monitoring of the planets HR 8799 b, c and d. We investigate how well the two simple cases of (i) a circular orbit and (ii) a face-on orbit fit the astrometric data for HR 8799 d over a total time baseline of ~2 years.
Methods. The HR 8799 planetary system was observed in L'-band with NACO at VLT.
Results. The results indicate that the orbit of HR 8799 d is inclined with respect to our line of sight, and suggest that the orbit is slightly eccentric or non-coplanar with the outer planets and debris disk.

Key words. planetary systems – stars: individual: HR 8799

1. Introduction

As the first and so far only directly imaged multiple exoplanet system, the HR 8799 system carries the promise of providing valuable insight into the structure and characteristics of planetary systems. While more than 500 extrasolar planets have now been discovered, most have been found by radial velocity and transit searches; the sample of known exoplanets is thus heavily biased towards short-period planets. Directly imaged giant extrasolar planets provide a necessary complement to these indirect detection techniques for a full picture of the characteristics of planets, and are crucial for theories of planet formation.

Challenging as it may be to directly image planets, whose relatively faint light is easily lost in the bright stellar glare, several confirmed companions are known. As of November 2010, 7 planetary mass objects belonging to stars, including the quadruple-planet HR 8799 system, have been discovered with direct imaging (Fomalhaut b, Kalas et al. 2008; β Pic b, Lagrange et al. 2009, 2010; 1RXS J160929.1-210524 b, Lafrenière et al. 2008, 2010, and HR 8799 bcde, Marois et al. 2008, 2010). The HR 8799 system is especially interesting since its multiple planet configuration allows for comparison of the characteristics of planets within the same environment of formation and evolution. The star is a young (30–160 Myr, Marois et al. 2008) A5 V star at at distance of 39.4 pc from the Sun (van Leeuwen 2007), surrounded by a debris disk (Rhee et al. 2007; Su et al. 2009). Three of the planets in the system, HR 8799 b, c and d, were discovered in 2008 and an additional planet, HR 8799 e, in 2010 (Marois et al. 2008, 2010), adding up to at least four giant planets of masses 7–10 M_J at projected separations 14.5, 24, 38 and 68 AU from the central star.

The astrometric analysis of the three outermost planets at the time of their discovery provided evidence that the planets are co-moving with the star, and suggested that their orbits are almost circular and seen close to face-on. However, dynamical modelling of the HR 8799 system has since shown that this initially presumed configuration of orbits is unlikely for reasons of orbital stability of the system (Fabrycky & Murray-Clay 2010; Reidemeister et al. 2009; Goździewski & Migaszewski 2009). Fabrycky & Murray-Clay (2010) found that for the masses derived by Marois et al. (2008) and circular, face-on orbits, the system would become unstable at an age of only $\sim 10^5$ years, i.e. significantly younger than its assumed present age. Stable mean motion resonance configurations were found for the three outer planets known at the time by Fabrycky & Murray-Clay (2010); Goździewski & Migaszewski (2009) and Reidemeister et al. (2009), and Marois et al. (2010) found stable resonant configurations including also the fourth planet.

In this paper, we present astrometric measurements of the three outermost planets in the HR 8799 system. The observations were obtained with NACO at VLT in September 2009 – one year after the discovery of planets b, c and d. We investigate how well two simple models with (i) a circular orbit and (ii) a face-on orbit fit the astrometric data when the new observations are included.

2. Observations and data reduction

Acquisition images of HR 8799 in L'-band were obtained with NACO/VLT (Lenzen et al. 2003; Rousset et al. 2003) on the nights of October 5 and 6, 2009, as part of the observation programme 084.C-0072, in which a spectrum of the planet HR 8799 c was obtained (Janson et al. 2010). The observations

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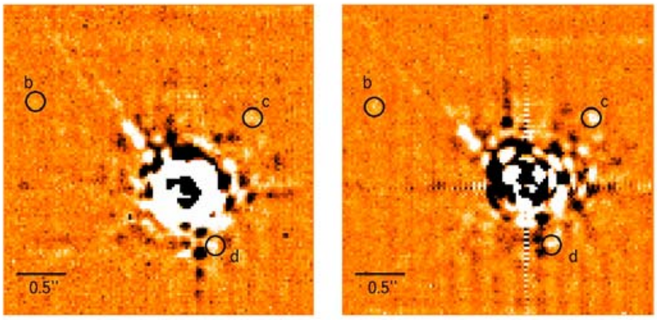

Fig. 1. NACO L'-band images of the HR 8799 system. Rotated and subtracted 3″ × 3″ images from observations on October 5 (*left*) and October 6 (*right*) 2009. North is up and east is to the left. Scaling is linear.

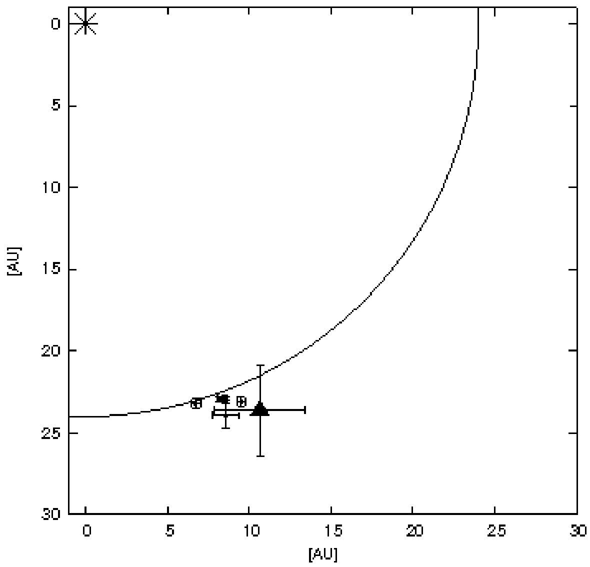

Fig. 2. Observations of HR 8799 d (see Table 1). A distance to the star of 39.4 pc is assumed, and the nominal circular, face-on orbit at 24 AU is overplotted. The star is marked with an asterisk at (0, 0). The triangle marks our NACO L' observation.

were acquired in cube-mode and consisted on each night of 2 sets of 10 data cubes, one set taken at the default orientation with north up and one rotated by 33°. The frames were obtained with the purpose of checking the alignment for slit orientation. Each cube contained 749 usable frames on October 5 and 1499 frames on October 6 with individual integration time 20.2 ms, yielding a total integration time of 15 s and 30 s respectively per data cube.

Images of the astrometric binary HD 211742 obtained in September 2009 were retrieved from the ESO (VLT) archive and used for calibration of plate scale and true north orientation of the detector. We derive a field rotation of –0.6° ± 0.2° and plate scale of 27.1 mas/px, consistent with the 27.2 mas/px of the L27 camera described in the NACO Usermanual, assuming a systematical error of 0.2° and 0.3 mas/px (1% of the pixel scale, see Köhler 2008).

The data reduction was performed using IRAF and IDL. Skyframes were constructed by averaging the sum frame of 10 data cubes obtained at the approximate same time and airmass with the star in different dither positions, rejecting the 2–3 highest values at each pixel in order to remove the stellar flux. The skyframes were subtracted from each frame in the cubes, and bad pixels were replaced by the mean value of neighbouring pixels. The frames were aligned by fitting a 2-D Gaussian to the star and measuring the centroid position, and then co-added to remove residual tip-tilt between individual frames of each data cube and produce one image per rotation angle for each night. Frames of poor quality or with the target too close to the detector edge, hence cutting out the planets, were rejected, resulting in a combination of 4–7 data cubes for each final image (4 images in total, one for each rotation angle on each night). Unsharp masking was used on the co-added frames by smoothing one version of the image using a boxcar average with 15 pixels and subtracting the smoothed image from the original. The positions of the planets and central star were determined using the IRAF *imexamine* task. While the brightest planet, HR 8799 c, was clearly detectable in all four images, the position of the fainter b-planet could only be determined from 3 measurements. Speckle contamination obscured planet d in the 33° rotated images and the position could thus only be determined from 2 frames. The reported position of planet e coincides with the third diffraction ring and is not detected with significant counts. Figure 1 shows rotated and subtracted images from both nights,

When imaging sources with vastly different spectral energy distributions through a broadband filter at an airmass >1.0, the effect of differential atmospheric refraction on the relative astrometry has to be considered (see, e.g., Hełminiak 2009). An effective wavelength $\lambda_{\rm eff} = 3.777\,\mu$m for our NACO L' imaging observation of the star HR 8799 was computed by convolving a spectrum of a star of similar spectral type from the IRTF SpeX spectral library (Cushing et al. 2005; Rayner et al. 2009) with the L' transmission curve from the NACO Usermanual. For the three exoplanets, an effective wavelength of $3.905 \pm 0.010\,\mu$m was computed using model spectra (Burrows et al. 2006, and priv. comm.) for an effective temperature of 1100 K and log g in the range 3.0 to 5.0.

As a consistency check, we also computed the effective wavelength for L' imaging observations of Jupiter based on the IRTF SpeX library, which resulted in $\lambda_{\rm eff} = 3.907\,\mu$m. Hence, once effective temperatures in the atmospheres of substellar objects are low enough to allow for the pronounced presence of water, methane and CO molecular absorption bands, the $\lambda_{\rm eff}$ values for L' observations seem to show little dependence on effective temperature and surface gravity.

Next, we used the model fits for the refractive index of humid air in the infrared as computed by Mathar (2007) to estimate the amplitude of differential atmospheric refraction of HR 8799 and its exoplanets. We found that this effect caused a shift of ≈5−6 mas of the planet positions along the parallactic angle. The positions of the planets relative to the star are presented in Table 1, together with all previously published position measurements. The errorbars were estimated by introducing artificial structures in the form of Gaussians with the same approximate peak flux and the same separations from the star as the real planets but at different angles. The deviations from the known positions were measured for a set of 3 different angles per planet and image. The standard deviations of all measurements for each "fake planet" are the estimated errors, mainly due to residual speckles for the two innermost planets.

3. Results and discussion

3.1. Astrometric measurements of HR 8799 b, c and d

The projected orbital motions of the two outermost planets b and c are slow (the periods are $P_{\rm b} \sim 460$ and $P_{\rm c} \sim 190$ years

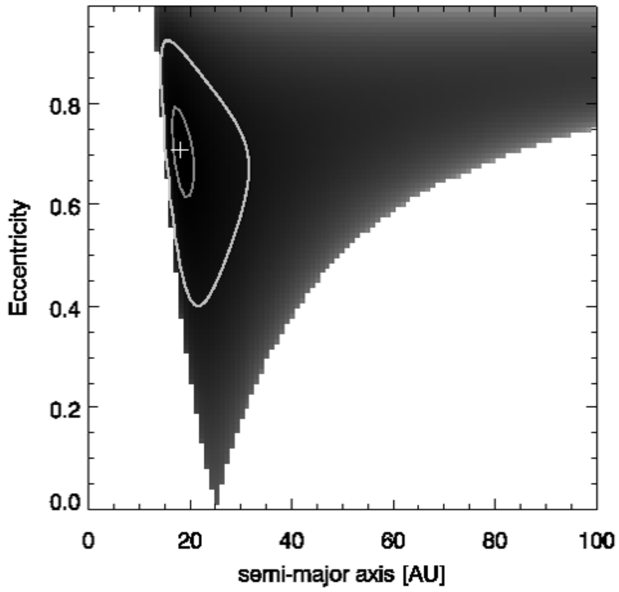

Fig. 3. χ^2-fit of eccentricity and semi-major axis for the orbit of HR 8799 d assuming $i = 0$ (face-on orbit). The best fit is marked by a cross and the contour lines show the 68.3% and 99.73% confidence regions.

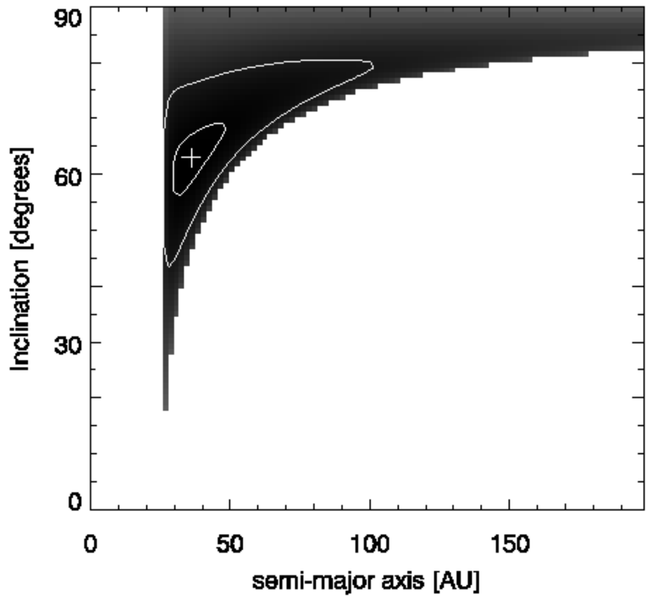

Fig. 4. χ^2-fit of inclination and semi-major axis for the orbit of HR 8799 d, assuming $e = 0$ (circular orbit). The best fit is marked by a cross, and the contour lines show the 68.3% and 99.73% confidence regions.

respectively, Marois et al. 2008), and the nominal mostly circular, face-on orbits are still consistent with observations when our data are added to the previously published astrometry. However, observations in 2008 and 2009 of planet d by Currie et al. (2011) and Hinz et al. (2010)[1] together with our observations suggest that the orbit of this planet might be eccentric and/or inclined. All published astrometric measurements of HR 8799 d are plotted in Fig. 2.

3.2. Testing the cases of i = 0 and e = 0 for HR 8799 d

We now want to test if the observed changes in position angle and separation are in agreement with different models. Fabrycky & Murray-Clay (2010) investigated the stability of different possible orbital families for the HR 8799 system. Many of these are for circular ($e = 0$) or face-on ($i = 0$) orbits. We modelled these two simple cases for HR 8799 d from the astrometric observations over a ~2 year time baseline. The nominal system mass of 1.5 $M_\odot$ (Marois et al. 2008) was used to compute orbital period from semi-major axis. We did not attempt to fit model orbits that are both inclined and eccentric, since this would add two free parameters and reduce the statistical significance of the result. For the following orbital fits we assumed errors as given in the literature and listed in Table 1. We note, however, that while the literature measurements are probably subject to systematic errors of the same order as the ones present in the VLT/NACO set, systematic errors (plate scale, detector orientation) between the different telescopes and instruments used are not necessarily included in these error bars.

[1] The MMT/Clio data by Hinz et al. (2010) were rereduced by Currie et al. (2011). We have adopted the Currie et al. (2011) astrometry for this analysis.

3.2.1. Face-on orbit model for HR 8799 d

Assuming a face-on orbit ($i = 0$) for HR 8799 d, the χ^2 was computed for a grid of 100 semi-major axes and 100 eccentricities and is shown in Fig. 3. The cross marks the best fit and the contour lines surround the 68.3% and 99.73% confidence regions. We find that a face-on orbit must have eccentricity $e \gtrsim 0.4$ to fit the observations with 99.73% confidence. The system should have become dynamically stable at the assumed age of 60 Myr, and one of the stability criteria of Fabrycky & Murray-Clay (2010) is that the orbits of the planets do not cross: $a_\mathrm{d}(1+e_\mathrm{d}) < 0.85a_\mathrm{c}(1-e_\mathrm{c})$. Our derived 99.73% confidence minimum eccentricity of $e \approx 0.4$ corresponds to an apastron distance of $r_\mathrm{ap}(d) \approx 34$ AU for the nominal semi-major axis of planet d at $a_\mathrm{d} = 24$ AU, thereby violating the mentioned stability criterium for the nominal orbit of planet c ($a_\mathrm{c} = 38$ AU). The stability criterium cannot be fulfilled with respect to both the outer planet c and the inner planet e even if the orbits of both c and e are perfectly circular. A face-on orbit is, with the astrometric data points taken at face value, unstable because of the high eccentricity, and not likely to represent the true orbit of the planet.

3.2.2. Circular orbit model for HR 8799 d

The case of zero eccentricity ($e = 0$) was considered by varying the orbital inclination and semimajor axis in the same way as described above. Figure 4 shows the χ^2 as a function of inclination and semi-major axis for a circular orbit. We find that the inclination is greater than 43° within the 99.73% confidence limits, with a best fit of $i = 63°$ and $a = 36$ AU. This is consistent with the asteroseismic constraints on the stellar rotational inclination of $i \gtrsim 40°$, with a best fit of $i = 65°$ derived by Wright et al. (2011). However, this inclination is higher than what has been derived for the orbit of planet b from a 10 year baseline of observations ($i \sim 13{-}23°$ for a circular orbit, Lafrenière et al. 2009), and also for the debris disk (3σ upper constraint, $i_\mathrm{disk} < 40°$, Moro-Martín et al. 2010). The observed configuration with four

Table 1. Relative positions of the HR 8799 planets.

Epoch	HR 8799b $\Delta\alpha$, $\Delta\delta$ (arcsec)	HR 8799c $\Delta\alpha$, $\Delta\delta$ (arcsec)	HR8799d $\Delta\alpha$, $\Delta\delta$ (arcsec)	HR8799e $\Delta\alpha$, $\Delta\delta$ (arcsec)	Reference
1998.83	1.411 ± 0.009, 0.986 ± 0.009	...	...	...	1
2002.54	1.481 ± 0.023, 0.919 ± 0.017	...	...	...	2
2004.53	1.471 ± 0.005, 0.884 ± 0.005	–0.739 ± 0.005, 0.612 ± 0.005	...	...	3
2007.58	1.522 ± 0.003, 0.815 ± 0.003	–0.672 ± 0.005, 0.674 ± 0.005	–0.170 ± 0.008, –0.589 ± 0.008	...	4
2007.81	1.512 ± 0.005, 0.805 ± 0.005	–0.674 ± 0.005, 0.681 ± 0.005	...	...	3
2008.52	1.527 ± 0.004, 0.799 ± 0.004	–0.658 ± 0.004, 0.701 ± 0.004	–0.208 ± 0.004, –0.582 ± 0.004	...	3
2008.61	1.527 ± 0.002, 0.801 ± 0.002	–0.657 ± 0.002, 0.706 ± 0.002	–0.216 ± 0.002, –0.582 ± 0.002	...	3
2008.71	1.528 ± 0.003, 0.798 ± 0.003	–0.657 ± 0.003, 0.706 ± 0.003	–0.216 ± 0.003, –0.582 ± 0.003	...	3
2008.89	1.532 ± 0.02, 0.796 ± 0.02	–0.654 ± 0.02, 0.700 ± 0.02	–0.217 ± 0.02, –0.608 ± 0.02	...	5
2009.58	...	...	...	–0.299 ± 0.019, –0.217 ± 0.019	6
2009.58	...	...	...	–0.303 ± 0.013, –0.209 ± 0.013	6
2009.62	1.536 ± 0.01, 0.785 ± 0.01	...	...	...	5
2009.70	1.538 ± 0.03, 0.777 ± 0.03	–0.634 ± 0.03, 0.697 ± 0.03	...	...	5
2009.76	1.535 ± 0.02, 0.816 ± 0.02	–0.636 ± 0.04, 0.692 ± 0.04	–0.270 ± 0.07, –0.600 ± 0.07	...	7
2009.77	1.532 ± 0.007, 0.783 ± 0.007	–0.627 ± 0.007, 0.716 ± 0.007	–0.241 ± 0.007, –0.586 ± 0.007	–0.306 ± 0.007, –0.217 ± 0.007	5
2009.83	...	...	...	–0.304 ± 0.010, –0.196 ± 0.010	6
2010.53	...	...	...	–0.325 ± 0.008, –0.173 ± 0.008	6
2010.55	...	...	...	–0.324 ± 0.011, –0.175 ± 0.011	6
2010.83	...	...	...	–0.334 ± 0.010, –0.162 ± 0.010	6

References. (1) Lafrenière et al. (2009); (2) Fukagawa et al. (2009); (3) Marois et al. (2008); (4) Metchev et al. (2009); (5) Currie et al. (2011); (6) Marois et al. (2010); (7) This work. Only statistical errors have been considered in the table.

visible planets around the star at very different position angles supports a low inclination, if the orbits are coplanar. With the astrometric data points taken at face value, the high inclination from the fit with $e = 0$ thus indicates that the orbital eccentricity of HR 8799 d is non-zero, or that the planetary orbits are non-coplanar.

4. Conclusions

The initial astrometric analysis performed by Marois et al. (2008) suggested mostly face-on and circular orbits for the three planets of HR 8799 known at the time. The orbital periods of the outermost planets b and c are of the order of hundreds of years, and with our additional astrometric measurements of these planets the orbits are still consistent with the nominal orbits.

Purely circular, face-on and coplanar orbits have been shown to be an unlikely configuration for reasons of dynamical stability (Fabrycky & Murray-Clay 2010; Goździewski & Migaszewski 2009; Reidemeister et al. 2009). Our analysis of the orbit of HR 8799 d implies that such a configuration is also inconsistent with the astrometric observations when recent observations by Hinz et al. (2010), Currie et al. (2011) and our NACO data are included. For a purely face-on orbit, the eccentricity of HR 8799 d is $e \gtrsim 0.4$ within 99.7% confidence. The system is not stable for such high e and the orbit is hence likely to be inclined with respect to our line of sight. In the case of a purely circular orbit we find that the inclination is $i > 43°$ within the 99.7% confidence limits. While the astrometric data is still limited, this result agrees well with recent constraints on the the stellar rotational inclination (Wright et al. 2011), but not with other measurements of the orbital inclination of planet b and the debris disk. The current astrometric data still allow for different orbital planes for the individual planets and the debris disk (and hence for non-coplanar orbits). Continued astrometric monitoring over a longer time baseline is required in order to put stronger constraints on the orbits of the HR 8799 planets.

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