ABSTRACT
Using the adaptive optics facilities at the 200-in Hale and 10-m Keck II, we observed in the near-infrared a sample of 12 binary and multiple stars and one open cluster. We used the near-diffraction-limited images of these systems to measure the relative separations and position angles between their components. In this paper, we investigate and correct for the influence of the differential chromatic refraction and chip distortions on our relative astrometric measurements. Over one night, we achieve an astrometric precision typically well below 1 mas and occasionally as small as 40 μas. Such a precision is in principle sufficient to astrometrically detect planetary mass objects around the components of nearby binary and multiple stars. Since we have not had sufficiently large data sets for the observed sample of stars to detect planets, we provide the limits to planetary mass objects based on the obtained astrometric precision.

Key words: instrumentation: adaptive optics – astrometry – binaries: visual – planetary systems.

1 INTRODUCTION
In the field of exoplanets, astrometry has not had too many triumphs to date. Of over 350 known planets or planetary candidates, only one has been discovered astrometrically (Pravdo & Shaklan 2009). The astrometric results presented by Han, Black & Gatewood (2001) are disputable and the true masses of only a few planets were calculated more reliably by combining the radial velocities (RV) and astrometry from the Hubble Space Telescope and the ground-based observations (Benedict et al. 2002, 2006). Nevertheless, astrometry may just turn out to be the most promising planet detection method in the future. Astrometric space missions, like Space Interferometry Mission (SIM) (Unwin et al. 2008) or Gaia (Perryman 2005), and a few ground-based interferometric surveys are ongoing (e.g. Lane & Muterspaugh 2004) or are in preparation (e.g. on the VLTI; Eisenhauer et al. 2008; Launhardt et al. 2008; Sahlman et al. 2008). In particular, ground-based interferometers seem to be already well suited to detect planets by providing microarcsecond (μas) astrometric precision (e.g. Muterspaugh et al. 2005) for bright nearby binary stars.

The milliarcsecond (mas) or better precision can be achieved by imaging with the adaptive optics (AO) systems. This was already demonstrated for two binaries, HD 19063 and HD 19994, observed with the VLT (Neuhäuser et al. 2006; Röll, Seifarth & Neuhäuser 2008) and a globular cluster M5 observed with the Hale telescope (Cameron, Britton & Kulkarni 2009). Such a precision can be reached by means of relative astrometry over a small field of view (Cameron et al. 2009). To this end, one needs to have at least one reference object not too far from a science object. For this reason, visual and speckle binaries become a natural target for such measurements. Incidentally, the subject of the existence of exoplanets in binary and multiple stars has become of significant interest (e.g. Raghavan et al. 2006; Eggenberger et al. 2007; Muterspaugh et al. 2007; Mugrauer & Neuhäuser 2009). It is now accepted that the detection or lack of planets in star systems will provide additional constraints to our models of planet formation (e.g. Holman & Weigert 1999; Nelson 2000; Lissauer et al. 2004).

In this paper, we present our observations of a sample of 12 binary and multiple stars and one open cluster obtained in 2002 with the AO facilities at the Hale and Keck II telescopes over the period of 7 months. We investigate the influence of several systematic effects that have an impact on the relative astrometry and demonstrate that by correcting them one can achieve a sub-mas precision. Finally, we provide the limits to planetary mass objects around components of our target stars derived from the obtained astrometric precision.

2 OBSERVATIONS
2.1 Instrumentation
The main instrument in our project was the 200-inch Hale Telescope at the Palomar Observatory. We used PHARO (the Palomar High Angular Resolution Observer; Hayward et al. 2001) camera with PALAO (the PALomar Adaptive Optics) system. PHARO uses
a mosaic of four 512 × 512 HgCdTe HAWAII detectors for observations between 1 and 2.5 μm (Hayward et al. 2001). PALAO is an AO system mounted at the Cassegrain focus of the telescope. It employs a Shack–Hartman wavefront sensor and a Xinetics Inc. 349/241 active-element deformable mirror. PALAO’s detailed description can be found online.1

With Hale/PALAO we obtained about 30 000 images of our targets. The data were collected over seven nights between 2002 April and November. We used an imaging mode with 39.91 and mostly 25.10 mas pixel−1 scale and K, K′, KS broad, as well as Brγ and FeII narrow band filters. We also used a 1 per cent transmission neutral density filter ND-1 for decreasing a flux from very bright stars. Dithering was carried out by shifting the observed position by ∼2 as.

We also had one clear night at the 10-m Keck II telescope. Using its AO system and NIRC2 (the Near InfraRed Camera 2) we obtained data for three targets and the total of about 600 images. NIRC2 is a mosaic of four 512 × 512 InSb Aladdin-3 detectors. For the observations we used 9.942 and 39.686 mas pixel−1 aperture and subtracted from the images of stars. As can be seen a simple and robust way of modelling the cores of stars’ images. One dimensional elliptical Gaussian function was fitted to the cores of the images of stars:

\[
G(x, y) = B + A \exp \left[ - \frac{[(x - x_0) \cos \theta - (y - y_0) \sin \theta]^2}{2\sigma_x^2} \right] - \frac{[(x - x_0) \sin \theta + (y - y_0) \cos \theta]^2}{2\sigma_y^2},
\]

where B is a background level, A is the amplitude of a Gaussian, (x0, y0) is a position of the star, \(\sigma_x\), \(\sigma_y\) are the corresponding widths and \(\theta\) is a tilt of the Gaussian.

We have decided to use such an approach because it offers a simple and robust way of modelling the cores of stars’ images. One could envision using an empirical point spread function (PSF) as a model for the images of stars. This is, however, challenging due to the fact that in a single image we typically have only two stars. Hence, our knowledge about the actual empirical PSF for a given frame is limited. Additionally, since the PSF’s shape varies, it is not practical to use several subsequent exposures as a reference for an averaged empirical. This is demonstrated in Fig. 3 for a series of five frames of GJ 661 taken on June 23 and spanning 15.5 min, for which an average empirical PSF is calculated using a 9 pixel aperture and subtracted from the images of stars. As can be seen a fitting of the Gaussian performs better. The details of this procedure are also given in Table 3.

The results of the Gaussian fitting were used to compute the relative separations and the position angles of pairs of stars. The NIRC2 data were corrected for the field rotation used for dithering. Let us note that we did not use any weighting scheme for individual

1 http://ao.jpl.nasa.gov/Palao/PalaoIndex.html
2 Two fainter stars seen close to GJ 300 and GJ 873 are actually field stars.
images as it was done by Cameron et al. (2009). A significant improvement in the astrometric precision after using an optimal weighting is seen when the number of reference stars exceeds five (see fig. 2 in Cameron et al. 2009) which is never the case in our work targeting binary stars and aimed at investigating the astrometric precision in the case of only one reference star.

4 SYSTEMATIC EFFECTS

4.1 Adaptive optics correction and field of view

The main factor allowing us to obtain precise astrometric measurements is obviously the AO. Its performance will influence the final astrometric precision as can be seen in the case of GJ 352 ($\rho \simeq 350$ mas) observed during challenging weather conditions. From all 75 images of GJ 352 taken, only the first 10 were properly corrected (the Airy pattern visible) and only in 53 images components were resolved and could be analysed. For these 53 images the centroids were calculated. Subsequent Gaussian fitting was possible only for 34 images for which the fitting procedure converged. The centroids and the outcome of Gaussian fitting are in agreement for the first 10 (Fig. 4).

Another factor having an impact on the astrometric precision is the field of view and the corresponding PSF sampling which was especially important for the Keck II data. The images were taken in two pixel scales (field sizes) – 9.942 mas pixel$^{-1}$.
(10 \times 10 \text{arcsec}^2 \text{ field, narrow}) \text{ and } 39.686 \text{ mas pixel}^{-1} \ (40 \times 40 \text{ arcsec}^2 \text{ field, wide}) \text{ and in various field rotator angles } -45.7, 0.7 \text{ and } -44.3. \text{ For this telescope the diffraction-limited size of a star's image in the near infrared corresponds to about 1.4 pixel in the wide field. For faint stars, it means that most of their light is collected in one pixel which makes the PSF undersampled and the Gaussian fitting difficult. This issue, however, can be at least partially overcome by a sub-pixel dithering. For the purpose of this paper, we used only the frames taken with the 'narrow' field.}

4.2 Atmospheric refraction

The atmospheric differential refraction (ADR) creates a shift of star's image. It is highly dependent on the zenith angle and wavelength. Formulae for computing ADR effect are given, for example, by Roe (2002) where the angle \( R \), which is the difference between the real and observed zenithal distance, is given by

\[
R \equiv z_t - z_a \simeq 206265 \left( \frac{n^2 - 1}{2n^2} \right) \tan z_t \ [\text{arcsec}],
\]

where \( z_t \) is the true zenithal distance, \( z_a \) is the observed zenithal distance and \( n \) is the refraction index, dependent on the wavelength \( \lambda \) and weather conditions:

\[
n(\lambda, p, T, p_w) = 1 + \left[ \frac{64.328 + \frac{29498.1}{146 - \lambda^2} + \frac{255.4}{41 - \lambda^2}}{p T_s} \right] \frac{p_w}{p_s} \times 10^{-6}
- 43.49 \left[ 1 - \frac{0.007956}{\lambda^2} \right] \frac{p_w}{p_s} \times 10^{-6},
\]

where \( p_T, p_w \) are the atmospheric pressures at the telescope and the diffraction limit, respectively.
where $\lambda$ is given in $\mu$m, $p$, $T$ and $p_w$ are the pressure [hPa], temperature [K] and partial pressure of water vapour, respectively. Symbols with the index $s$ refer to the canonical values of air pressure (1013.25 hPa) and temperature (288.15 K). The angle $R$ is much smaller in IR than in visible.

ADR also affects relative astrometric measurements. Since two objects are seen at different zenithal distances $z_1$ and $z_2$, the corrections $R_1$ and $R_2$ are also different. The component of the separation, vector parallel to the direction to the zenith, increases after ADR correction by $R = |R_2 - R_1|$. This quantity changes with weather conditions (air pressure and temperature). As we have demonstrated (Helminiak 2009), the magnitude of this change is often higher than an achievable astrometric precision even for relatively compact systems. Clearly, ADR’s influence must be corrected and the weather conditions should be well known. This conclusion is in contrary to that by Neuhäuser et al. (2006), who claim that the refraction is, in general, insignificant, thanks to the use of a narrow bandpass filter (chromatic refraction). As the ADR is dependent on the zenithal distance, it may be significant even for a monochromatic light. So, the real reason why ADR is negligible in case of Neuhäuser et al. (2006) is likely the geometry of their binary. Nevertheless, it is true that using wide-band filters makes ADR harder to calculate due to its chromatic character and, for example, stars’ different colours (Helminiak 2009).

Unfortunately, we did not collect any weather readings during our observing runs, so we had to use the canonical values of temperature and pressure, and assumed 50 per cent humidity. For the Keck observations we assumed two times smaller pressure and the temperature of 0°C. This means that the real uncertainties of measured separations and position angles are higher than the precisions given in Table 6. To correct for ADR, we used the semifull approach as described by Helminiak (2009).

In order to estimate the maximum error due to ADR, we took the largest possible separation in our sample – 30.8 as for GJ 873 1-2 (from Table 6). We assumed that the difference in the zenithal angles equals the separation, and the binary is seen 30° above the horizon. In such an improbable case, the maximum contribution to the error budget coming from the temperature is 4 mas (if the real temperature were $T = 230$ K and pressure $p = 1013.25$ hPa) and the fraction coming from the air pressure is smaller than 8 mas (for $p = 613$ hPa and $T = 230$ K). One should add that the bigger the part coming from the temperature, the smaller is the contribution from the pressure. So we may conclude that in this improbable case 8, mas is the maximum error and in most (if not all) of our real observations the uncertainty caused by the weather conditions is smaller than several mas. In the case of binaries observed with Keck II, the maximum error should be much smaller because the separations (and $z$ differences) are smaller and other, more probable weather conditions were assumed. The maximum uncertainty scales linearly with air pressure and almost linearly with separation (maximum $z$ difference) and temperature. In Section 5.1 we estimate, in yet another way, the observed rms of our astrometric measurements.

### 4.3 Chip geometry and orientation

Detectors are not perfectly rectangular, flat and perpendicular to the light path. At the astrometric precision necessary to detect planets (well below 1 mas), one has to know how the camera’s detector is distorted or how the pixel scale and the detector’s orientation change from epoch to epoch. For instruments mounted in the Cassegrain focus, as is the case for PHARO, the distortion changes with the telescope’s position due to gravity. This effect is not present or negligible in the case of NIRC2 which is located in a Nasmyth platform. The astrometric calibration and distortion models are available for both cameras. The calibration for PHARO is more complicated and includes not only the geometry and orientation of the detector itself but also the influence of telescope’s position and tilt of the chip relative to the light path. This is described by Metchev (2006).\(^3\) The distortion of the NIRC2 camera was investigated during its pre-shipping testing and is described by Thompson, Egani & Sawicki (2001).\(^4\)

The calibration we carried out included deriving the average plate-scale of the chip and the position of the north direction with respect to the Cassegrain ring (CR). The nominal values are 25.10 mas pixel\(^{-1}\) for the narrow, 39.91 mas pixel\(^{-1}\) for the wide field pixel scale and 335.8 for CR (Hayward et al. 2001). As it was shown by Metchev & Hillenbrand (2004), the real values are different from the nominal one and usually change from epoch to epoch. As a base for our calibration, we adopted the measurements from 2002 June 23 by Metchev & Hillenbrand (2004) which are: 25.168 ± 0.034 mas pixel\(^{-1}\) and 334.043 ± 0.099. We chose four stars in NGC 6871, marked in Fig. 1 as 1–4 which we believe to be members of the cluster (their positions with respect to the star No. 5 changed in a similar way), and using their relative positions we have recalculated the average pixel scale in the narrow field by assuming that their astrometric motion is not detectable. First of all, for every night and every six possible pairs, we calculated a preliminary pixel scale and the north direction, incorporating the uncertainties from Metchev & Hillenbrand (2004). Later, we averaged the results for every single night. We checked if for two or more consecutive nights the pixel scale changed, and if it did not, we averaged the

---

\(^3\) See http://www.astro.ucla.edu/~metchev/ao.html

\(^4\) See http://alamoana.keck.hawaii.edu/inst/nirc2/preship_testing.pdf
Table 2. Basic information on our targets.

| Star No. | Sp. type | Magn. (Band) | \(\pi\) (mas) | Comment\(^a\) | Telescope | Ref. |
|----------|----------|--------------|---------------|--------------|-----------|------|
| 56 Per B | 1+2      | ???          | 8.7           | 24.00 (.91)  | Double    | Keck II | 1,2  |
| GJ 195 A | 1        | M1           | 10.16         | 72.0(4)      | –         | Hale    | 3,4  |
| GJ 195 B | 2        | M5           | 13.7          | 72.0(4)      | –         | Hale    | 3,4  |
| AG+45 517| 3        | ???          | 11 (V)        | ???          | Field     | Hale    | 4    |
| GJ 300 B | 1+2      | K7II?        | 8.39 (J)      | 125.60 (.97) | Double, field | Keck II | 5,6  |
| GJ 352 B | 1        | M4           | 10.07 (V)     | 94.95 (4.31) | –         | Hale    | 1.7  |
| GJ 352 A | 1        | M4           | 10.08 (V)     | 94.95 (4.31) | –         | Hale    | 1.7  |
| GJ 458 A | 1        | M0.5         | 9.86          | 65.29 (1.47) | –         | Hale    | 1.8  |
| GJ 458 B | 2        | M3           | 13.33 (V)     | 65.29 (1.47) | –         | Hale    | 1.8  |
| GJ 507 A | 1        | M0.5         | 9.52          | 75.96 (3.31) | –         | Hale    | 1    |
| GJ 507 B | 2        | M3           | 12.09 (V)     | 75.96 (3.31) | –         | Hale    | 1    |
| GJ 569 Ba | 1       | M8.5V        | 11.14 (J)     | 101.91 (1.67) | Double(?\(^b\)) | Keck II | 1,9,10,11 |
| GJ 569 Bb | 2       | M9V          | 11.65 (J)     | 101.91 (1.67) | –         | Keck II | 1,9,11 |
| GJ 661 A | 1        | M3           | 10.0 (V)      | 158.17 (3.26) | –         | Hale    | 1.7  |
| GJ 661 B | 2        | M4           | 10.3 (V)      | 158.17 (3.26) | –         | Hale    | 1.7  |
| GJ 767 B | 1        | M1           | 10.28 (V)     | 74.90 (2.93) | –         | Hale    | 1.8  |
| GJ 767 B | 2        | M2           | 11.10 (V)     | 74.90 (2.93) | –         | Hale    | 1.8  |
| GJ 860 A | 1        | M3           | 9.59          | 249.53 (3.03) | Variable | Hale    | 1,12 |
| GJ 860 B | 2        | M4           | 10.30 (V)     | 249.53 (3.03) | Flare     | Hale    | 1,12 |
| CCDM 22281...H\(^c\) | 3 | ???          | 13.8 (V)      | ???          | Field     | Hale    | 13   |
| GJ 873 A | 1        | M3.5e        | 10.09 (V)     | 198.07 (2.05) | Flare     | Hale    | 1    |
| GJ 873 B | 2+3      | G            | 10.66 (V)     | 198.07 (2.05) | Double, field | Hale    | 1,14 |
| GJ 9071 A | 1       | K7           | 10.2 (V)      | 72(4)        | –         | Hale    | 1,8,13 |
| GJ 9071 B | 2       | M0           | 14 (B)        | 72(4)        | –         | Hale    | 1,13 |

\(^a\)If ‘double’, magnitude refers to a total magnitude of both components and spectral type is ‘averaged’. If ‘field’, the star is not gravitationally tied with brighter components.

\(^b\)Parallax is for GJ 300, not the two investigated stars.

\(^c\)Simon, Bender & Prato (2006) suggested that GJ 569 Ba may be a binary with similar brightness components.

\(^d\)CCDDM 22281...H = CCDM J22281+5741H – a part of a multi-stellar system which includes also GJ 860.

Ref.: (1) The Hipparcos Catalogue (Perryman et al. 1997); (2) Barstow et al. (2001); (3) Jenkins (1952); (4) The PPM North Catalogue (Roeser & Bastian 1988); (5) Simons, Henry & Kirkpatrick (1996); (6) Henry et al. (2006); (7) Al-Shukri et al. (1996); (8) Reid et al. (2004); (9) Lane & Muterspaugh (2004); (10) Simon et al. (2006); (11) Cutri et al. (2003); (12) Law, Hodgkin & McKay (2008); (13) CCDM - Catalog of Components of Double & Multiple stars (Domanget & Nys 2002); (14) Oppenheimer et al. (2001).

This binary was also observed in the wide field mode on April 23 at the beginning of the night. By combining the measurements from the wide and narrow fields, we obtained 40.00 ± 0.02 mas pixel\(^-1\) as a pixel scale for the wide field and noticed no change in the CR angle. Between June and November, we noticed two changes of the CR orientation. The values of CR for August and November were 334:072 ± 0.011 and 334:723 ± 0.015, respectively. The recalculated value for June 24 and 26 was 334:039 ± 0.018. We should also note that the position angles were computed from Δx and Δy counted in pixels along the chip’s axes, so the bigger the separation, the smaller is the uncertainty in θ.

Values of the derived plate-scale and north positions are summarized in Table 4. For the stars in the open cluster NGC 6871, we show the average values of separations together with their rms’ (Table 5, Fig. 5). The average values are calculated from five epochs corrected for the new pixel scales. Such a calibration is not perfect, and these plate-scale and north direction values are subject to possible systematic errors, for example, due to a limited knowledge of the weather conditions.

Examples of the distortion and the results of employing its model can be seen in Fig. 6. We show the uncorrected and corrected measurements of separation (Δx, Δy) for two stars in the NGC 6871 field. The distortion is clearly seen in the x-axis (the top-left panel). It is worth noting that for PHARO the distortion is much bigger in x than in y, but in the y-axis the random scatter is about 50 per cent.

result over the number of nights. This procedure allowed us to improve our pixel scale’s uncertainties with respect to those given by Metchev & Hillenbrand (2004) who used only one pair while we used up to 18 (six pairs, observed during three nights). An adequate procedure was carried out for the CR orientation angle.

For three nights of 2002 August and November, we obtained the value of 25.156 ± 0.010 mas pixel\(^-1\) which is in poor agreement with the previous value, but then the difference in separations of the stars was clearly seen. We also recalculated new pixel scale for June 24 and obtained 25.171 ± 0.021 mas pixel\(^-1\) which shows that there was actually no scale change during one night. We also assumed the same plate-scale for the night of June 26. The cluster NGC 6871 was not observed in 2002 April but the results for GJ 458 suggest that the pixel scale and orientation were the same as in June. We assumed that the orbital period of GJ 458 is long enough that no orbital motion can be seen after 62 days and the separation remains constant. Comparing this system with GJ 195, which is closer to the Sun and has a few times smaller angular separation, we may conclude that the period is much longer than 338 years (orbital period of GJ 195; Heintz 1974), probably close to 3200 years. We see only a small (however clear) motion in GJ 195, and we should expect at least a 10 times smaller movement in GJ 458 which would be below the detection. Thus, for 2002 April we used the same pixel scale as for June 23 with its relatively high uncertainty.
Figure 3. Top left: a combined image of GJ 661 from five exposures taken on June 23. The corresponding frame numbers are next to each image of the binary. Top right: a residual image after a subtraction of an empirical PSF (computed with DAOPHOT; Stetson 1987). The size of the fitting aperture (9 pixel in radius) is shown as a white circle. Upper middle: a 15 \times 15 pixel zooms on the contour plots of the fitted Gaussian functions at the positions of respective stars. Contour levels vary. Gaussians clearly show significant variations of their shape. Lower middle: the same zooms on the residuals after the subtraction of the Gaussian functions. Changes of the first Airy ring can be seen. Colour scale is the same in every sub-panel. Bottom: the same zooms on the residuals after a subtraction of an empirical PSF. A clear leftover in the PSF core is evident. Colour scale is the same in every sub-panel.

bigger. The histograms demonstrate that after the correction, we are able to obtain a Gaussian statistics (the middle panels), and the Allan variance (AV) shows no obvious signs of systematic errors (the bottom panels).

The real average plate-scales of NIRC2 were found to be in agreement with the nominal values (Metchev & Hillenbrand 2004) but the y-axis was rotated by 1:24 clockwise from north (Metchev et al. 2005). Unfortunately, due to a small number of useful images in our data set, we were not able to perform proper tests and our own calibrations. Hopefully, the location of the camera on the Nasmyth platform grants its stability. In particular, the results for 56 Per and GJ 569 B where three different field rotator positions were used demonstrates that the precision of the field rotator of NIRC2 is better than 0.1 during one night.

5 ASTROMETRY

The astrometric measurements are presented in Table 6, where for each pair of stars and epoch (MJD) the separation $\rho$ [mas] and the position angle $\theta$ [in degree] are given. The 1\(\sigma\) errors were calculated using the Gaussian statistic of $\Delta x$ and $\Delta y$. The plate-scale uncertainty is included into the separation error, but not into $\Delta \theta$ for Hale observations. It is because we wanted to show how small changes can be noticed between two nights where the same chip orientation is present (see GJ 860 1-2 in August – MJD = 52509 and 52510). CR orientation uncertainties are about one order of magnitude bigger, so they would dominate the $\theta$ error budget. The uncertainty in $\theta$ for GJ 300 is also underestimated because this system was observed with only one position of the field rotator of
Table 3. Parameters of an elliptical Gaussian function used to model the images of stars in the frames for GJ 661 (Fig. 3). An average value of a residual after a Gaussian and an empirical PSF subtraction are given together with its uncertainties in the last four columns. Analyzed frames are numbered as in Fig. 3.

| Star frame/ID | A (counts) | σ_x (pixel) | σ_y (pixel) | x_0 (pixel) | y_0 (pixel) | B (counts) | θ (°) | Av. resid. (G) | σ | Av. resid. (PSF) | σ |
|---------------|------------|-------------|-------------|-------------|-------------|------------|-------|----------------|----|----------------|----|
| No. 50/1      | 2846.443   | 1.505       | 1.432       | 543.897     | 615.032     | 13.231     | 130   | 17.59          | 18.16 | −111.73         | 13.57 |
| No. 50/2      | 2203.045   | 1.437       | 1.429       | 548.635     | 588.264     | 48.128     | 91    | 3.74           | 11.38 | −101.62         | 10.73 |
| No. 100/1     | 2711.196   | 1.399       | 1.499       | 622.879     | 694.661     | −0.042     | 122   | 4.88           | 11.46 | −39.33          | 5.68  |
| No. 100/2     | 2125.978   | 1.378       | 1.512       | 627.583     | 667.851     | −0.300     | 125   | −3.95          | 14.32 | −85.35          | 7.45  |
| No. 150/1     | 2629.679   | 1.478       | 1.407       | 626.141     | 538.949     | 35.679     | 16    | 11.13          | 11.38 | −130.78         | 10.17 |
| No. 150/2     | 1953.843   | 1.636       | 1.527       | 630.955     | 512.050     | −17.370    | 65    | 15.58          | 17.12 | −116.19         | 17.75 |
| No. 200/1     | 2391.502   | 1.395       | 1.488       | 462.866     | 453.715     | 59.381     | 122   | 4.88           | 11.46 | −39.33          | 5.68  |
| No. 200/2     | 1928.833   | 1.363       | 1.469       | 467.544     | 508.818     | 51.934     | 65    | 8.88           | 13.26 | −75.02          | 7.67  |
| No. 250/1     | 2344.759   | 1.436       | 1.349       | 626.177     | 652.063     | 81.791     | 165   | 2.47           | 7.87  | −112.96         | 9.03  |
| No. 250/2     | 1722.767   | 1.441       | 1.450       | 630.861     | 625.335     | 50.023     | 87    | 0.83           | 6.09  | −67.74          | 7.36  |

Figure 4. Impact of AO correction on relative position measurements in case of GJ 352. After image No. 107 (dashed line) AO works improperly.

Table 4. Average pixel scales and north orientations for Hale telescope.

| Night          | Scale (mas pixel⁻¹) | North (°) |
|----------------|---------------------|-----------|
| Apr. 23 (narrow) | 25.168 (34)         | 334.043 (99) |
| Apr. 23 (wide)   | 40.00 (2)           | 334.043 (99) |
| Jun. 23          | 25.168 (34)         | 334.043 (99) |
| Jun. 24          | 25.171 (21)         | 334.039 (18) |
| Jun. 26          | 25.171 (21)         | 334.039 (18) |
| Aug. 21          | 25.156 (10)         | 334.072 (11) |
| Aug. 22          | 25.156 (10)         | 334.072 (11) |
| Nov. 13          | 25.156 (10)         | 334.723 (15) |

Table 5. The average separations between the stars 1 to 4 in the NGC 6871 open cluster.

| Pair | ρ (mas) | rms |
|------|---------|-----|
| NGC 6871 1–2 | 2171.719 | 0.604 |
| 1–3 | 6906.003 | 0.533 |
| 1–4 | 11303.461 | 1.023 |
| 2–3 | 5257.245 | 0.302 |
| 2–4 | 11463.147 | 1.194 |
| 3–4 | 16144.625 | 1.019 |

NIR2C. This is, however, not the case for 56 Per and GJ 569 B where different values of the field rotator were used for dithering. Hence, the resulting formal error of the position angle, presumably, more realistically reflects the accuracy of this AO system. For systems observed more than once, the orbital, parallactic and proper motion can be seen. Even for the long-period binary GJ 195 ($P \approx 338$ yr; Heintz 1974), there is a clear signature of the orbital motion. Also a closer inspection of GJ 873 reveals a motion of the double secondary system (see Fig. 8). GJ 873 B is probably a real binary but at a different distance from the Sun than GJ 873 A (parallactic motion is present).

For five of our binaries (GJ 195, GJ 352, GJ 569 B, GJ 661 and GJ 860), the orbital solutions are known and can be found in the Washington Double Star Catalog (WDS). The corresponding orbital elements are presented in Table 7. The quality of the orbit is represented by the parameter $q$ – the smaller the value, the more accurate is the orbital solution. In all the five cases the orbital solutions are not perfect, but only for GJ 195 the elements are poor due to a long period of the binary.

5 Sixth Catalog of Orbits of Visual Binary Stars http://ad.usno.navy.mil/wds/orb6/orb6frames.html
Figure 5. Separations of stars from the open cluster NGC 6871. The average value is plotted as a solid line and the corresponding rms in mas is shown.

Figure 6. An example of the distortion and its correction for two stars in NGC 6871 cluster. Left-hand panels refer to X (α) component, right ones to Y (δ). Top panels: the measurements before (+) and after (x, shifted) the distortion correction. Middle panels: the histograms of the measurements (bin width of 0.05 pixel) with a Gaussian fitted to the corrected measurements (left). Bottom panels: the AV of the uncorrected (dot-dashed) and corrected (solid) measurements and an infinitely long, white-noise signal with σ given in the middle panel (dotted line).
Table 6. Separations and position angles of investigated stars.

| Pair     | \( \rho \) (mas) ± | \( \theta \) [°] ± | MJD | Pair     | \( \rho \) [mas] ± | \( \theta \) [°] ± | MJD |
|----------|---------------------|-----------------|-----|----------|---------------------|-----------------|-----|
| 56 Per B |                     |                 |     | GJ 767   |                     |                 |     |
| 1–2      | 626.31 0.32         | 291.733 0.039   | 52337 | 1–2      | 5276.64 0.17       | 135.4224 0.0014 | 52509 |
| 2–3      | 13895.74 0.43       | 52.8881 0.0013  | 52509 | 2–3      | 2875.365 0.048     | 84.0420 0.0014  | 52450 |
| 1–2      | 12152.38 0.23       | 126.3902 0.0008 | 52509 | 1–2      | 2875.849 0.078     | 84.0520 0.0014  | 52450 |
| 1–2      | 13954.70 0.24       | 52.6982 0.0008  | 52509 | 1–2      | 2858.542 0.061     | 83.2373 0.0010  | 52509 |
| 2–4      | 9699.14 0.51        | 112.6419 0.0024 | 52509 | 2–4      | 2858.621 0.061     | 83.2063 0.0009  | 52509 |
| 3–4      | 12303.86 0.50       | 189.9677 0.0034 | 52509 | 3–4      | 2625.54.5 0.73     | 133.9775 0.0012 | 52450 |
| GJ 860   |                     |                 |     | GJ 352   |                     |                 |     |
| 1–2      | 2035.74 0.12        | 66.6688 0.0018  | 52337 | 1–2      | 25139.60 0.13      | 137.4185 0.0019 | 52509 |
| 1–2      | 346.21 1.11         | 113.6970 0.12   | 52389 | 1–2      | 24771.78 0.75      | 139.0745 0.0012 | 52450 |
| GJ 458   |                     |                 |     | GJ 458   |                     |                 |     |
| 1–2      | 14723.58 0.40       | 10.55272 0.00024 | 52389 | 1–2      | 30155.85 0.57      | 47.0269 0.0009  | 52450 |
| 1–2      | 14720.19 0.28       | 10.56016 0.00016 | 52450 | 1–2      | 30158.79 1.07      | 47.0469 0.0016  | 52450 |
| 1–2      | 14723.27 0.36       | 10.55398 0.00021 | 52451 | 1–2      | 30328.74 0.73      | 47.2967 0.0012  | 52509 |
| GJ 507   |                     |                 |     | GJ 507   |                     |                 |     |
| 1–2      | 17747.73 0.45       | 131.0180 0.0012 | 52389 | 1–2      | 29089.44 0.58      | 45.8990 0.0009  | 52450 |
| 1–2      | 17757.84 0.33       | 131.0927 0.0006 | 52450 | 1–2      | 29093.40 0.85      | 45.9219 0.0013  | 52450 |
| 1–2      | 17756.96 0.66       | 131.0845 0.0013 | 52451 | 1–2      | 29260.32 0.76      | 46.1888 0.0012  | 52509 |
| GJ 569 B |                     |                 |     | GJ 661   |                     |                 |     |
| 1–2      | 98.14 0.11          | 61.506 0.050    | 52337 | 1–2      | 1215.619 0.067     | 255.1128 0.0034 | 52450 |
| GJ 661   |                     |                 |     | GJ 9071  |                     |                 |     |
| 1–2      | 724.611 0.079       | 195.3279 0.0015 | 52389 | 1–2      | 1214.012 0.347     | 255.0787 0.0170 | 52509 |
| 1–2      | 685.264 0.170       | 192.2382 0.0023 | 52450 | 1–2      | 1214.012 0.347     | 255.0787 0.0170 | 52509 |
| 1–2      | 685.065 0.044       | 192.1392 0.0007 | 52451 | 2–3      | 1214.913 0.085     | 255.0884 0.0044 | 52509 |
| 1–2      | 683.084 0.038       | 192.0158 0.0006 | 52454 | 1–2      | 1215.301 0.100     | 255.0963 0.0048 | 52509 |
| 1–2      | 643.316 0.058       | 188.7846 0.0006 | 52509 | 1–2      | 9971.76 0.20       | 239.5226 0.0009 | 52509 |
| 1–2      | 642.957 0.041       | 188.7072 0.0004 | 52510 | 1–2      | 9924.03 0.24       | 240.6097 0.0011 | 52509 |

Table 7. Orbital elements of five of our binaries for which orbital solutions are available from WDS.

| Star     | \( P \) (yr) | \( a \) (mas) | \( e \) | \( i \) [°] | \( \Omega \) [°] | \( \Omega_1 \) [°] | \( \tau \) (MJD) | WDS ID |
|----------|--------------|---------------|--------|----------|---------------|------------------|-----------------|--------|
| GJ 195  | 338.90       | 3720          | 0.0    | 65.1     | 168.51        | 0.0              | 55197           | 05167+4600 5 |
| GJ 352  | 18.42        | 630.09        | 0.29   | 14.3     | 48.27         | 285.0            | 45663           | 09313+1329 3 |
| GJ 569B | 2.424        | 90.40         | 0.312  | 32.4     | 321.3         | 256.7            | 51821           | 14545+1606 2 |
| GJ 661  | 12.9512      | 762.0         | 0.743  | 149.14   | 160.0         | 99.0             | 48373           | 17121+4540 2 |
| GJ 860  | 44.67        | 2383          | 0.41   | 167.2    | 154.5         | 211.0            | 40666           | 22280+5742 2 |
In Fig. 7, the comparison between the orbit and our measurements is shown. There are several possible sources of the discrepancy between our data and the orbits: (1) the quality of the orbits; (2) the uncertainty in the pixel scale; (3) an imperfect ADR correction. The level of the discrepancies (~100 mas for GJ 195 and GJ 860, ~20 mas for GJ 352) seems to favour the first explanation. Also, if the cause was the ADR correction, one would expect a much higher scatter (see the next section).

5.1 Overnight and long-term astrometric precision

During one night, for most of the binaries observed with the Hale telescope we were able to go down below 500 μas in astrometric precision of ρ and in some cases below 100. As expected, the precision is better for objects for which more single images were obtained. For pairs with similar brightness of the components, the astrometric error is smaller than for pairs with a high brightness difference. This is due to the poor S/N of the faint component as well as a need not to saturate the bright one. It is imaginable that the usage of weighting might improve the precision a little.

In some cases when the stars are located on two different parts of the chip’s mosaic, the astrometric errors are larger. In particular, for a very frequently observed, relatively close binary GJ 661 we achieved the highest overnight precision of 38 μas. Despite the fact that in this case the distortion correction is not perfect due to a...
location of the binary around the centre of the chip where all four parts of the mosaic meet, Metchev (2006) suggest not to use this area because of small differences in the chip’s components geometry. It seems possible that for a binary like GJ 661, one may be able to achieve a precision even below our 38 μas in one night.

We achieved a similar level of overnight precision with the Keck II/NIRC2. The main difference between the two data sets is the significantly lower number of images. It is quite surprising that with 10 frames taken with the ‘narrow’ camera we reached ~120 μas precision for GJ 300. Nevertheless, one should treat this value cautiously. A low number of useful images does not allow for a particularly accurate calibration.

Three systems GJ 661, GJ 860, GJ 873 and the open cluster NGC 6871 were observed more frequently than the remaining targets. Using their measurements, we can estimate the astrometric accuracy of the Hale telescope over a 120–140 d time span. For the open cluster we take only pairs with star No. 5 which we believe is not a member of the cluster. Having five or six (for GJ 661) epochs, we can fit a second-order polynomial to the measured separations. Such a polynomial is sufficient to model the proper, parallactic and orbital motion of a close pair of stars. The fits are shown in Fig. 8. The rms’ for all fits are collected in Table 8. Note that again the resulting rms’ are worse for pairs with very high brightness ratios such as those for GJ 860 with the star no. 3 and GJ 873 with the star no. 1. These rms’ are also obviously higher than single night precisions for the corresponding pairs of stars and can be treated as an estimate for the true astrometric errors incorporating systematic effects due to an imperfect plate-scale calibration, limited knowledge of the weather conditions and long-term astrometric stability of the telescopes/cameras which could not be accounted for with our limited calibrations.

5.2 Detection limits

The astrometric signal, Θ (μas), of a planet with a semimajor axis \( a \) (au) and mass \( M_P \) (Jupiter masses) in a circular orbit around a star at a distance \( d \) (parsecs) and mass \( M_S \) (solar units) is given by (Pravdo & Shaklan 1996)

\[
\Theta = 1920 \frac{a M_P}{d M_S}.
\]

(4)

Obviously, the same relation can be used for an S-type planet\(^6\) in a wide binary system. Assuming that an astrometric signal above \( 3 \sigma_\rho \) can be treated as a real one, Θ in equation (4) may be replaced by \( 3 \sigma_\rho \) (mas) (from Table 6). After changing \( d \) (pc) to parallax \( \pi \) (mas) we obtain

\[
a M_P [au M_J] = \frac{1562.5 \sigma_\rho M_S}{\pi}.
\]

(5)

In the above \( a M_P = 4 \) [au \( M_J \)] means that we can detect 1 \( M_J \) (or more massive) planet in 4 au (or wider) orbit, or 2 \( M_J \) planet in 2 au orbit, etc.

\(^6\) S-type, or satellite-type planet in binary/multiple is a planet orbiting only one of the components (Dvorak 1984).
The detection limits for the binaries, in which at least one stellar mass is known or can be estimated, are collected in Table 9. Subscripts I and II refer to the order of stars given in the first column. As one can see, in principle, it is possible to achieve a sufficient astrometric precision to detect a massive planet or a brown dwarf with the Hale and Keck telescopes. As we have demonstrated in the previous section, currently a longer term precision is up to several times lower than the one achieved over one night. However, one can
Table 8. The rms of second-order polynomial fits to the measurements of $\rho$ for the most frequently observed objects.

| Pair     | rms (mas) | No. of nights | Time span (d) |
|----------|-----------|---------------|---------------|
| GJ 661 1–2 | 0.282     | 6             | 122           |
| GJ 661 1–3 | 2.154     | 5             | 143           |
| GJ 661 2–3 | 2.595     |               |               |
| GJ 873 1–2 | 1.127     | 5             | 143           |
| GJ 873 1–3 | 1.282     |               |               |
| GJ 873 2–3 | 0.309     |               |               |
| NGC 6871 1–5 | 0.872 | 5             | 143           |
| NGC 6871 2–5 | 0.717 |               |               |
| NGC 6871 3–5 | 0.763 |               |               |
| NGC 6871 4–5 | 2.671 |               |               |

use the rms' from Table 8 with equation (5) and compute long-term planetary detection limits. These long-term limits' are also listed in Table 9.

6 CONCLUSIONS

Nearby binary and multiple star systems are excellent targets for astrometric searches for extrasolar planets, thanks to their proximity and the availability of natural reference stars necessary for relative astrometry. In our study of 12 visual binaries/multiples and one open cluster with the Hale and Keck II telescopes and their adaptive optics facilities, we have demonstrated that over one night one is able to obtain an astrometric precision reaching $\sim$40 $\mu$as. Such a precision is sufficient to detect Jupiter mass planets around components of binary and multiple stars. However, in order to turn the precision into a long-term accuracy required to detect planets, one must be able to account for ADR and the plate-scale changes. The ADR correction requires accurate weather readings and the plate-scale changes must be carefully calibrated. In our attempt to account for both, we were able to achieve a long-term (over a 140 d time-span) accuracy ranging from 0.2 to 2.7 mas, that is several times larger than the corresponding overnight precision, but still allowing for detection of massive planets or brown dwarfs. Since we have had limited means to carry out the calibrations, it is quite possible that a higher long-term accuracy can be reached with the existing AO facilities.

Table 9. $a M_P$ limits.

| Pair     | $\pi$ (mas) | $M_I$ (M$\odot$) | $M_H$ (M$\odot$) | $\sigma_\rho$ (mas) | MJD | $a_1 M_P I$ [au $\cdot$ M$\odot$] | $a_2 M_P II$ [au $\cdot$ M$\odot$] | Ref. |
|----------|-------------|-----------------|-----------------|---------------------|-----|-------------------------------|-------------------------------|-----|
| GJ 195 1–2 | 72.0        | 0.53            | 0.19            | 0.31                | 52509 | 3.56                          | 1.28                          | 1   |
|          |             |                 |                 | 0.23                | 52510 | 2.65                          | 0.95                          |     |
|          |             |                 |                 | 0.12                | 52592 | 1.38                          | 0.50                          |     |
| GJ 195 1–3 | 0.53        | –               | 0.50            | 0.44                | 52592 | 5.06                          | –                             | 1   |
|          |             |                 |                 | 0.24                | 52592 | 2.76                          | –                             |     |
| GJ 195 1–4 | 0.53        | –               | 0.54            | 0.47                | 52592 | 5.41                          | –                             | 1   |
|          |             |                 |                 | 0.23                | 52592 | 2.64                          | –                             |     |
| GJ 195 2–3 | 0.19        | –               | 0.43            | 0.46                | 52592 | 1.77                          | –                             | 1   |
|          |             |                 |                 | 0.24                | 52592 | 0.99                          | –                             |     |
| GJ 195 2–4 | 0.19        | –               | 0.51            | 0.47                | 52592 | 2.10                          | –                             | 1   |
|          |             |                 |                 | 0.21                | 52592 | 0.87                          | –                             |     |
| GJ 352 1–2 | 94.95       | 0.44            | 0.41            | 1.11                | 52389 | 8.04                          | 7.49                          | 2   |
| GJ 458 1–2 | 65.29       | 0.40            | 0.37            | 0.40                | 52389 | 3.83                          | 3.54                          | 3   |
|          |             |                 |                 | 0.28                | 52450 | 2.68                          | 2.48                          |     |
|          |             |                 |                 | 0.36                | 52451 | 3.45                          | 3.19                          |     |
| GJ 507 1–2 | 75.96       | 0.46            | 0.37            | 0.45                | 52450 | 3.70                          | 3.43                          | 3   |
|          |             |                 |                 | 0.33                | 52450 | 3.12                          | 2.51                          |     |
|          |             |                 |                 | 0.36                | 52451 | 6.25                          | 5.03                          |     |
| GJ 569B 1–2 | 101.91     | 0.071           | 0.054           | 0.11                | 52337 | 0.012                         | 0.009                         | 4   |
| GJ 661 1–2 | 158.17      | 0.379           | 0.34            | 0.079               | 52389 | 0.30                          | 0.29                          | 5   |
|          |             |                 |                 | 0.170               | 52450 | 0.63                          | 0.62                          |     |
|          |             |                 |                 | 0.044               | 52451 | 0.17                          | 0.16                          |     |
|          |             |                 |                 | 0.038               | 52454 | 0.16                          | 0.15                          |     |
|          |             |                 |                 | 0.058               | 52509 | 0.22                          | 0.21                          |     |
|          |             |                 |                 | 0.041               | 52510 | 0.17                          | 0.16                          |     |
|          |             |                 |                 | 0.282               | Total | 1.05                          | 1.03                          |     |

ACKNOWLEDGMENTS

MK is supported by the Foundation for Polish Science through a FOCUS grant and fellowship. This work was supported by the Polish Ministry of Science and Higher Education through grants N203 005 32/0449 and 1P03D-021-29, and by NASA through grant NNG04GM62G.

This publication made use of data products from the Two-Micron All Sky Survey, which is a joint project of the University of
| Pair   | $\pi$ (mas) | $M_I$ ($M_{\odot}$) | $M_{II}$ ($M_{\odot}$) | $\sigma_\rho$ (mas) | MJD | $a_I M_{P,I}$ [au $\cdot M_{\odot}$] | $a_{II} M_{P,II}$ [au $\cdot M_{\odot}$] | Ref. |
|--------|-------------|---------------------|------------------------|---------------------|-----|--------------------------------|---------------------------------|-----|
| GJ 767 1–2 | 74.9        | 0.44                | 0.4                    | 0.17                | 52509 | 1.56                           | 1.42                            | 3   |
|        |             |                     |                        | 0.12                | 52510 | 1.10                           | 1.00                            |     |
|        |             |                     |                        | 0.09                | 52592 | 0.83                           | 0.75                            |     |
| GJ 767 1–3 | 0.44        | –                   | 0.52                   | 0.43                | 52509 | 4.77                           | –                               | 3   |
|        |             |                     |                        | 0.28                | 52510 | 2.57                           | –                               |     |
|        |             |                     |                        | 0.39                | 52592 | 3.58                           | –                               |     |
| GJ 767 2–3 | 0.4         | –                   | 0.43                   | 0.22                | 52510 | 1.83                           | –                               | 3   |
|        |             |                     |                        | 0.35                | 52592 | 2.92                           | –                               |     |
| GJ 860 1–2 | 249.53      | 0.34                | 0.2711                 | 0.078               | 52450 | 0.17                           | 0.13                            | 5   |
|        |             |                     |                        | 0.048               | 52451 | 0.10                           | 0.09                            |     |
|        |             |                     |                        | 0.061               | 52509 | 0.13                           | 0.10                            |     |
|        |             |                     |                        | 0.061               | 52510 | 0.13                           | 0.10                            |     |
|        |             |                     |                        | 0.087               | 52592 | 0.18                           | 0.15                            |     |
|        |             |                     |                        | 0.216               | Total | 0.45                           | 0.37                            |     |
| GJ 860 1–3 | 0.34        | –                   | 0.73                   | 0.41                | 52451 | 0.86                           | –                               | 3   |
|        |             |                     |                        | 0.94                | 52509 | 2.01                           | –                               |     |
|        |             |                     |                        | 1.37                | 52510 | 2.95                           | –                               |     |
|        |             |                     |                        | 1.34                | 52592 | 2.86                           | –                               |     |
|        |             |                     |                        | 2.154               | Total | 4.60                           | –                               |     |
| GJ 860 2–3 | 0.2711      | –                   | 0.75                   | 0.42                | 52451 | 1.28                           | –                               | 5   |
|        |             |                     |                        | 0.91                | 52509 | 1.29                           | –                               |     |
|        |             |                     |                        | 1.19                | 52510 | 2.02                           | –                               |     |
|        |             |                     |                        | 1.33                | 52592 | 2.54                           | –                               |     |
|        |             |                     |                        | 2.595               | Total | 4.96                           | –                               |     |
| GJ 873 1–2 | 0.36        | –                   | 0.57                   | 1.07                | 52451 | 1.62                           | –                               | 3   |
|        |             |                     |                        | 0.73                | 52509 | 2.07                           | –                               |     |
|        |             |                     |                        | 0.60                | 52510 | 1.71                           | –                               |     |
|        |             |                     |                        | 1.12                | 52592 | 3.20                           | –                               |     |
|        |             |                     |                        | 1.127               | Total | 3.29                           | –                               |     |
| GJ 873 1–3 | 198.07      | 0.36                | 0.58                   | 0.85                | 52451 | 1.65                           | –                               | 3   |
|        |             |                     |                        | 0.76                | 52509 | 2.41                           | –                               |     |
|        |             |                     |                        | 0.61                | 52510 | 2.16                           | –                               |     |
|        |             |                     |                        | 1.03                | 52592 | 2.93                           | –                               |     |
|        |             |                     |                        | 1.282               | Total | 3.65                           | –                               |     |
| GJ 9071 1–2 | 72          | 0.53                | 0.49                   | 0.20                | 52509 | 2.22                           | 2.05                            | 3   |
|        |             |                     |                        | 0.26                | 52510 | 2.89                           | 2.67                            |     |
|        |             |                     |                        | 0.24                | 52592 | 2.66                           | 2.46                            |     |

References: (1) Fischer & Marcy (1992); (2) Söderhjelm (1999); (3) Harmanec (1988); (4) Zapatero Osorio et al. (2004); (5) Delfosse et al. (2000).

Note: If MJD is 'Total', the limit refers to the rms of the fit given in Table 8 – an estimate of a long-term astrometric precision for a given pair of stars.

Massachusetts and the Infrared Processing and Analysis centre California Institute of Technology, funded by the NASA and the National Science Foundation.

REFERENCES

Al-Shukri A. M., McAlister H. A., Hartkopf W. I., Hutter D. J., Franz O. G., 1996, AJ, 111, 393
Barstow M. A., Bond H. E., Burleigh M. R., Holberg J. B., 2001, MNRAS, 322, 891
Benedict G. F. et al., 2002, ApJ, 581, L115
Benedict G. F. et al., 2006, AJ, 132, 2206
Cameron P. B., Britton M. C., Kulkarni S. R., 2009, AJ, 137, 83
Cutri R. M. et al., 2003, The IRSA 2MASS All-Sky Point Source Catalog, NASA/IPAC Infrared Science Archive.
http://irsa.ipac.caltech.edu/applications/Gator/
Delfosse X., Forveille T., Segransan D., Beuzit J.-L., Udry S., Perrier C., Mayor M., 2000, A&A, 364, 217
Dommanget J., Nys O., 2002, Observations et Travaux, 54, 5
Dvorak R., 1984, Celest. Mech., 34, 369
Eggenberger A., Udry S., Chauvin G., Beuzit J.-L., Lagrange A.-M., Segransan D., Mayor M., 2007, A&A, 474, 273
Eisenhauer F. et al., 2008, IAU, 248, 100
Fischer D. A., Marcy G. W., 1992, ApJ, 396, 198
Han I., Black D. C., Gatewood G., 2001, ApJ, 548, L57
Harmanec P., 1988, Bull. Astron. Inst. Czech., 39, 329

© 2009 The Authors. Journal compilation © 2009 RAS, MNRAS 400, 406–421
