Astrometric search for extrasolar planets in stellar multiple systems

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Abstract

Using ground based large telescopes like the ESO/VLT in Chile (8m), we observe nearby stellar multiple systems and monitor their separation and position angle over the time very precisely by relative astrometry. Our goal is to detect extrasolar planets in binaries and triple systems in order to improve our understanding of observational biases and selection effects in the sample of extrasolar planets known today. Observing our targets with AO assisted near infrared imagers, we are able to study binaries over a wide range of apparent semi-major axis from about five AU up to thousand AU. This allows us to search for exoplanets in "forbidden" binary systems with semi-major axes smaller than about 18 AU, where from the theoretical point of view the close stellar component should inhibit planet formation. By using a near infrared narrow-band filter to suppress differential chromatic refraction effects and observing a globular cluster to monitor the astrometric stability of our imager, we achieve a long-term astrometric precision of about 0.1 mas, sufficient to detect the astrometric signal of Jovian exoplanets around sun-like stars and Neptune-like exoplanets around low-mass stars.

As a first result, we detected the astrometric signal of a further higher mass object in the HD19994 exoplanet host binary. Our astrometric detection is confirmed by speckle-interferometry as well as spectroscopic follow-up observations. Thus, HD19994 is a triple system where an exoplanet orbiting the stellar primary.

1. Astrometric search of extrasolar planets

Currently, about 450 exoplanets are detected, most of them by radial velocity or transit measurements. Today, it is generally known that every search method has its own observational bias and selection effect. For example, taking our own solar system as an archetype, most of the exoplanet search programs today concentrate on single and sun-like stars. As one can clearly see in Fig. 1, every observation method covers a specific area in the parameter-space. Transiting exoplanets are mainly found as Jovian planets with an orbital periods of less than one week, while most of the radial velocity exoplanets are Jovian-like with an orbital period ranging from days to several years. But there is a huge white region in the parameter space, a detection gap for exoplanets with larger orbital radius, where neither radial velocity nor transit measurements are sensitive enough. This region, to the lower right in the mass-period diagram, can be perfectly filled with exoplanet detections by astrometry.
By searching exoplanets in stellar multiple systems with astrometry, we try to answer the question, if the multiplicity of stars affect planetary formation and if so, how this influence looks like. Fig. 2 shows the statistical analysis of exoplanets around single stars and in stellar multiple systems. While the analysis of the mass-period relation is biased by the increasing number of transiting exoplanets (no conclusion can be made), there seems to be a real statistical significant difference between both samples for the eccentricity-period relation.

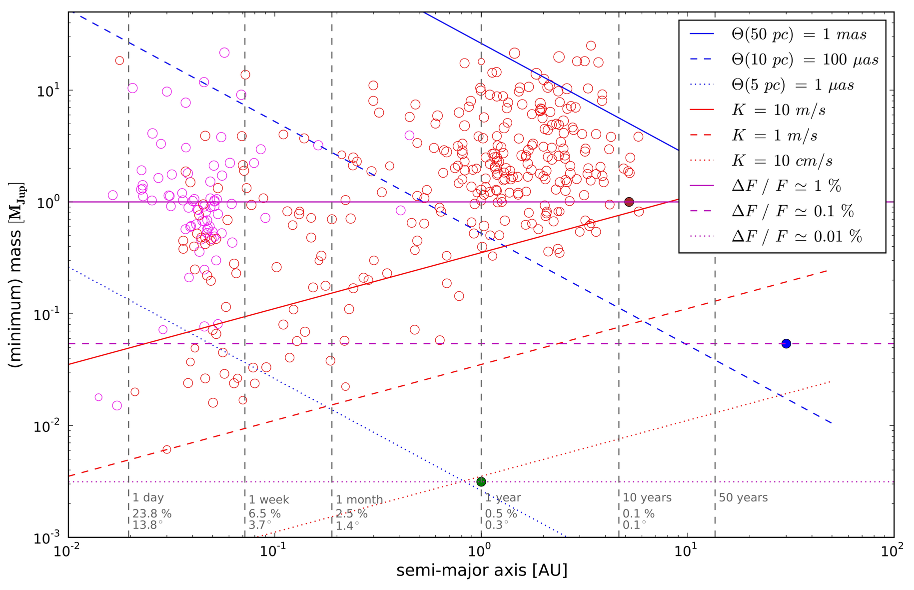

Figure 1: *The diagram shows the (minimum) mass over the planetary semi-major axis of all exoplanets detected so far (based on Extrasolar Planets Encyclopedia) with the radial velocity technique (red circles) and transit observations (magenta circles). The size of the symbols represents the mass of the exoplanet host star. The lines indicate the radial velocity signal (red lines), the transit signal (magenta lines) and the astrometric signal (blue lines) of an exoplanet orbiting a sun-like star. Furthermore, Jupiter (brown dot), Neptune (blue dot) and Earth (green dot) are displayed. The gray lines are selected orbital periods with a certain probability to detect a transit signal of an exoplanet orbiting a sun-like star. The lower number is the maximum allowed difference of the planetary inclination from an edge-on (i.e.* $i = 90°$*) orbit. Clearly detectable is the large white region with no exoplanet detections at the lower right region for larger planetary periods. This region can be perfectly filled by astrometric observations, which are, in contrast to radial velocity and transit measurements, mainly sensitive for such large orbital periods.*

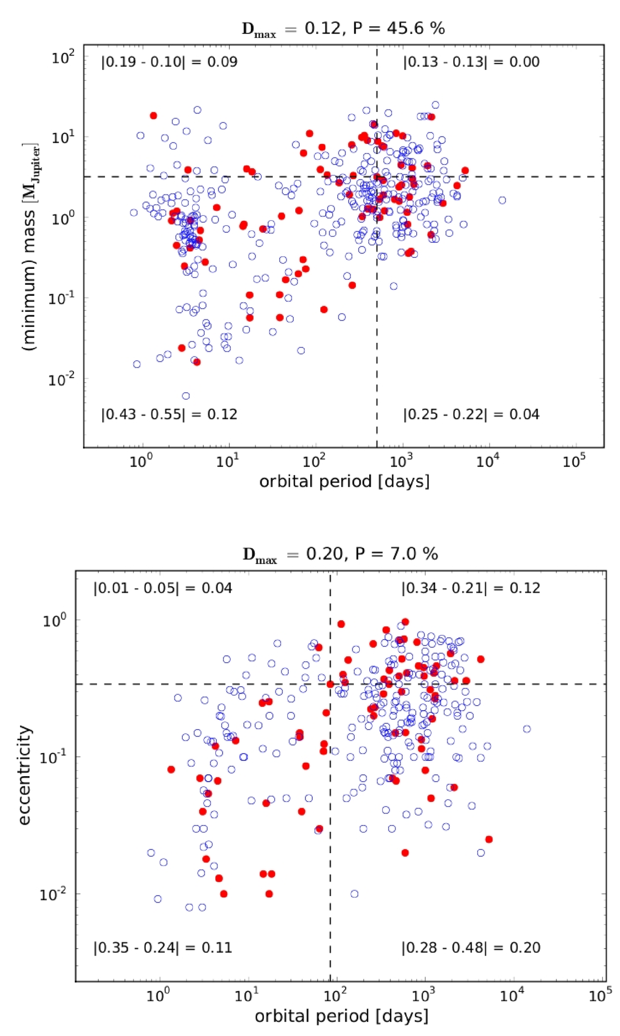

Figure 2: *Two-dimensional Kolmogorov-Smirnov-Test to check for a unique parent distribution of exoplanets in stellar multiple systems (red dots) and exoplanets around single stars (blue circle). While for the mass-period relation (top) the probability for both samples having the same parent distribution is about 50%, it is lower than 10% for the eccentricity-period relation (bottom).*

2. Astrometric observations of stellar multiple systems

Our targets are nearby ($d \leq 100\,\mathrm{pc}$) stellar multiple systems, mainly binaries and triple systems. We choose suitable systems with no known exoplanets as well as with known exoplanets in order to confirm them by an astrometric signal. Covering the semi-major axis range from several to thousand AU and by including also systems with late-type stars, we are able to systematically analyze exoplanet properties with respect to the stellar system properties, like host-star mass and separation.

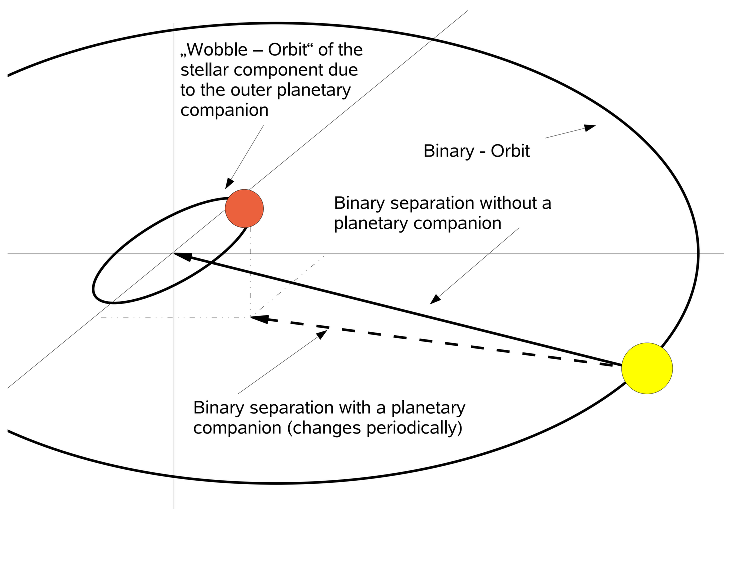

Figure 3: *Sketch of an unseen astrometric companion orbiting one stellar component of a binary. The reflex motion (also called "wobble") of this stellar component can be detected as a period change of the binary's separation and position angle. Due to the large orbital period differences of a visual binary and an astrometric companion, these periodic changes can easily be distinguished from the binary influence.*

The full (peak-to-peak) astrometric wobble θ to be expected for a circular orbit can be calculated as

$$\theta\,[\mathrm{mas}] = 1.91 \times \frac{\mathrm{a}\,[\mathrm{AU}]}{\mathrm{d}\,[\mathrm{pc}]} \times \frac{\mathrm{M_{pl}}\,[\mathrm{M_{Jup}}]}{\mathrm{M_\star}\,[\mathrm{M_\odot}]}.$$

In the case of a non-negligible brightness of the astrometric companion, the observed wobble is the reflex motion of the combined flux-center around the common center of mass (semi-major axis $\alpha_\star$) and has to be corrected to the reflex motion of the star itself (semi-major axis $\mathrm{a}_\star$) by

$$\mathrm{a}_\star = \alpha_\star \left(1 - \frac{\mathrm{F}}{\mathrm{B}}\right)^{-1}$$

where B is the fraction of mass and F the fraction of luminosities.

$$\mathrm{B} = \frac{\mathrm{m_{comp}}}{\mathrm{m_{comp}} + \mathrm{M_\star}}$$

$$\mathrm{F} = \frac{\mathrm{L_{comp}}}{\mathrm{L_{comp}} + \mathrm{L_\star}} = \left(1 + 10^{0.4\,\Delta\mathrm{m}}\right)^{-1}$$

3. First result: The exoplanet host binary HD19994 - now a triple system

At the end of 2009, we observed one of our targets, the exoplanet host-system HD19994, for the fourth time. Due to the stellar binary orbit itself, which also affects the binary separation and position angle and which we handle as a second order polynomial, we need at least four measurements before we are able to check our data for an astrometric signal. HD19994 is a stellar binary with an F8V as primary ($\mathrm{M} \simeq 1.3\,\mathrm{M_\odot}$), where Mayor et al. (2004) discovered a radial velocity exoplanet with a minimum mass of $\simeq 2\,\mathrm{M_{Jup}}$ and a M3V as secondary star ($\mathrm{M} \simeq 0.3\mathrm{M_\odot}$) with a separation of about 2 arcs. Our goal was to detect the astrometric signal of HD19994 Ab, which would be in the range of $\simeq 0.1 \ldots 1\,\mathrm{mas}$, depending on the orbital orientation. However, what we found in our data was a signal of about 8 mas, far to large for the exoplanet, which leads us to the assumption of a further and higher mass component around HD19994 B. To confirm our assumption we analyzed our NaCo cube mode data with speckle-interferometry using a program written by R. Köhler (see Fig. 6) and started spectroscopic follow-up observations with the high resolution NIR spectrograph CRIRES by A. Seifahrt and J. Bean (see Fig. 7). Both techniques confirm our astrometric detection of an additional body orbiting HD19994 B, but also point to a higher brightness and a higher eccentricity for the new C component compared to the astrometric fit results, thus the mass as well as the shape of the reflex-orbit have to be corrected. However, the astrometric signal is real and prefigure (together with speckle and spectral data) a low-mass star for the new C component orbiting HD19994 B within about 669 days.

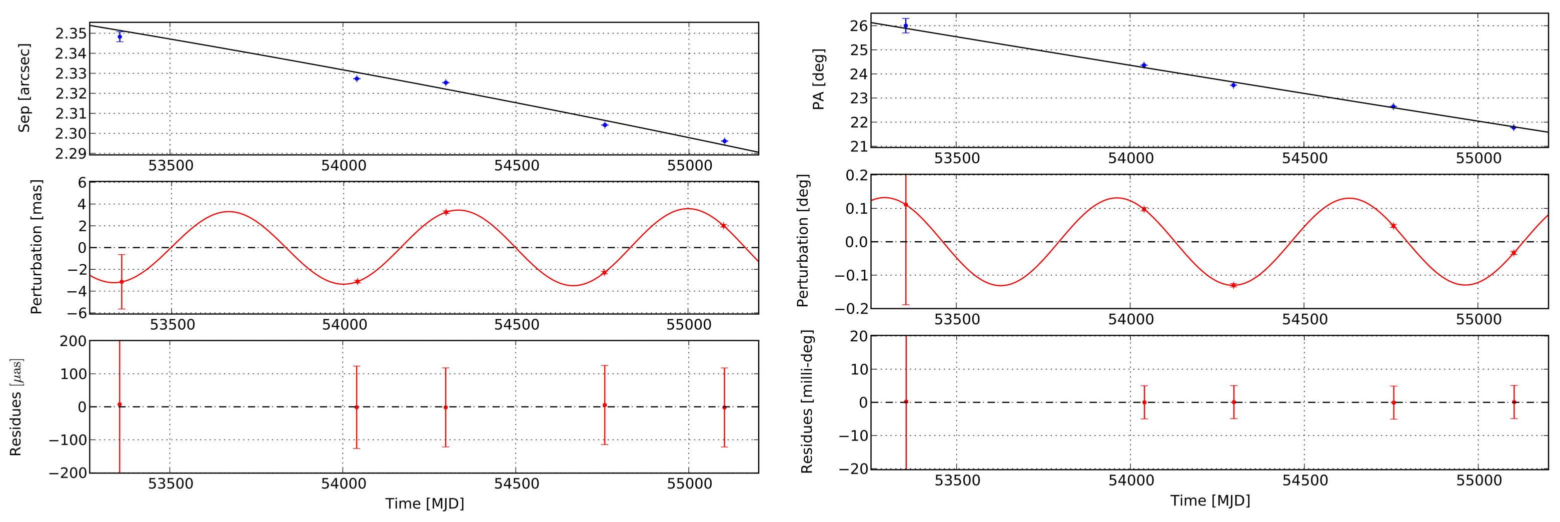

Figure 4: *Separation and position angle measurements of HD19994 A & B from 2004, 2006, 2007, 2008 and 2009. The upper bottom also include a second order polynomial as a stellar binary influence. Deviations and a model for a further astrometric component around HD19994 B is plotted in the middle panel. At the bottom the residues to the astrometric companion model is shown. In 2004 no astrometric calibration cluster was observed, which results in larger error bar.*

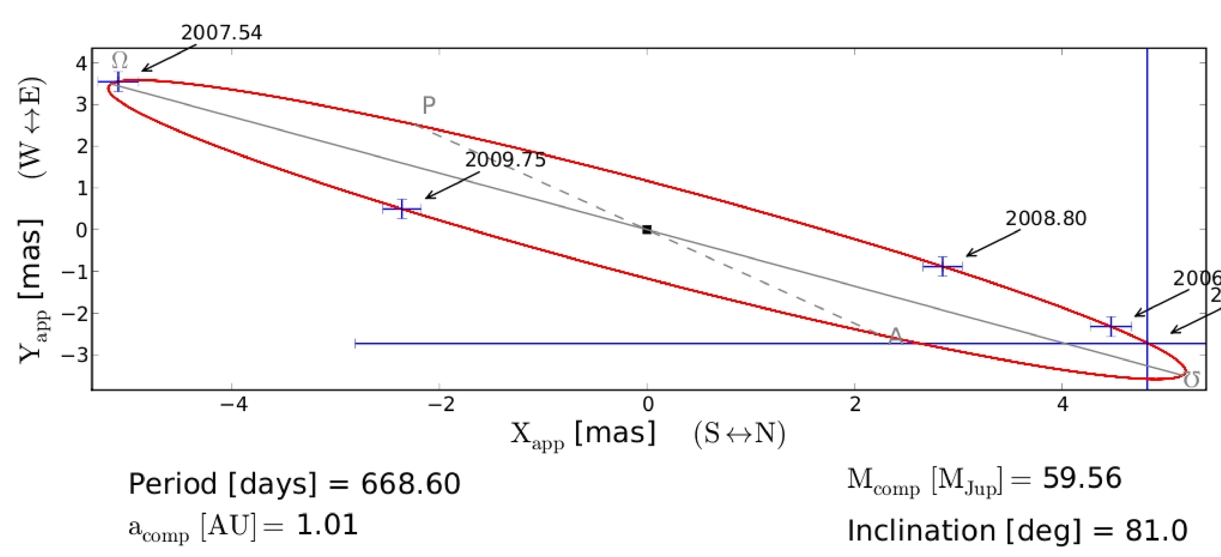

Figure 5: *Reconstructed reflex-orbit of HD19994 B based on the measured separation and position angle changes of HD 19994 A & B, whereas the stellar binary influence of HD19994 B around A was fitted as a second order polynomial by* χ^2 *minimization. Hence, the obtained orbital solution assumes a circular orbit of the astrometric companion around B. Furthermore, the obtained mass of the astrometric companion based on a negligible luminosity and has to be corrected in case of an effectual brightness of the astrometric companion.*

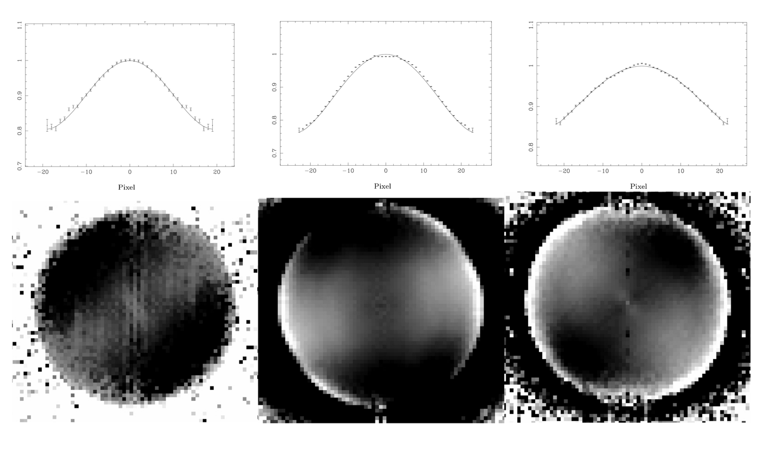

Figure 6: *Complex visibilities of HD19994 B for 2007, 2008 and 2009 (from left to right) obtained with speckle-interferometry using a program written by R. Köhler (Köhler et al., 2008). One can clearly see the existence of a further object orbiting the B component, which indicates a non-negligible luminosity of the proposed C component. Thus, the orbit and mass given in Fig. 5 have to be corrected regarding the brightness ratio, which will likely result in a low-mass star instead of a high-mass brown dwarf for the detected astrometric companion.*

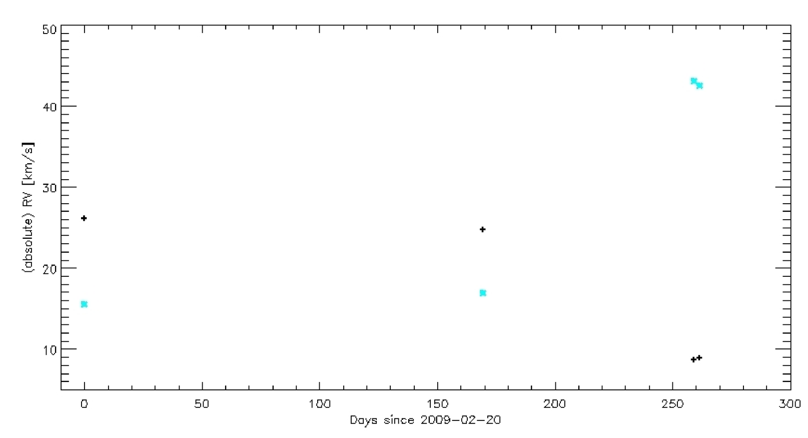

Figure 7: *Preliminary radial velocity measurements of HD 19994 B, which turned out to be a spectroscopic binary itself (black cross: B component, turquoise cross: C component), obtained with CRIRES by A. Seifahrt and J. Bean. These measurements indicate also a brighter astrometric companion and furthermore a higher eccentricity of the C component. Thus, the orbital shape shown in Fig. 5 is not correct and has to be re-fitted including the measurements from speckle-interferometry and spectroscopic observations. The radial velocities indicate a mass ratio of about 0.5 for HD19994 B and C.*

4. Conclusions

- Astrometry is a useful method to detect exoplanets with larger orbital periods and in stellar multiple systems.
- With our search program we are able to study exoplanets in e.g. binaries with apparent separations from about 5 AU up to 1000 AU.
- Due to the sensitivity for larger orbital periods, astrometric search programs have a larger observational timeline than radial velocity or transit search programs.
- An astrometric calibration system to monitor the astrometric stability as well as the use of a near infrared narrow band filter are indispensable for ground-based observations.
- Our first target system - the exoplanet host binary HD19994 - turned out to be a triple system. Our astrometric detection of the new C component is confirmed by speckle analysis as well as spectroscopic follow-up observations.
- A final fit (including the measurements of all three techniques) is on the way, but HD19994 C seems to be a low-mass star.

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