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ESPRI: Astrometric planet search with PRIMA at the VLTI

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Abstract. The ESPRI consortium will conduct an astrometric survey for extrasolar planets, using the PRIMA facility at the Very Large Telescope Interferometer. Our scientific goals include determining orbital inclinations and masses for planets already known from radial-velocity surveys, searches for planets around nearby stars of all masses, and around young stars. The consortium has built the PRIMA differential delay lines, developed an astrometric operation and calibration plan, and will deliver astrometric data reduction software.

1. INTRODUCTION

Extrasolar planets have become the subject of many studies during the past one and a half decades. Monitoring of the radial velocity and brightness of thousands of stars has revealed the presence of more than 400 planets, which betray their existence through the gravitational interaction with their parent star, or through transits in front of the stellar disk. For non-transiting planets the product of their mass and the sine of the orbital inclination, $m \sin i$, can be derived from radial-velocity measurements; the combination of data from both techniques yields the mass for transiting objects. Both techniques are strongly biased towards the detection of planets in short-period orbits. Astrometry offers an alternative approach to the detection and characterization of extrasolar planets, with better sensitivity to long-period orbits, and the capability to determine the mass of non-transiting planets.

Ground-based astrometry is limited by the Earth's atmosphere, but measurements with a precision of tens of microarcseconds are possible relative to reference stars located nearby on the sky. The precision of such narrow-angle data improves with the aperture diameter, making interferometry with baselines of $\sim$100 . . . 200 m an attractive option. In this paper, we describe the preparations for an astrometric planet survey with the European Southern Observatory's Very Large Telescope Interferometer (VLTI), by the ESPRI consortium.

2. INTERFEROMETRIC ASTROMETRY

Astrometric observations by interferometry are based on measurements of the delay $D = D_{\rm int} + (\lambda/2\pi)\phi$, where $D_{\rm int} = D_2 - D_1$ is the internal delay measured by a metrology system (see Fig. 1), and ϕ the observed fringe phase (see e.g. Quirrenbach 2001 and references therein). D is related to the baseline $\vec{B}$ by

$$D = \vec{B} \cdot \hat{s} = B \cos \theta, \qquad (1)$$

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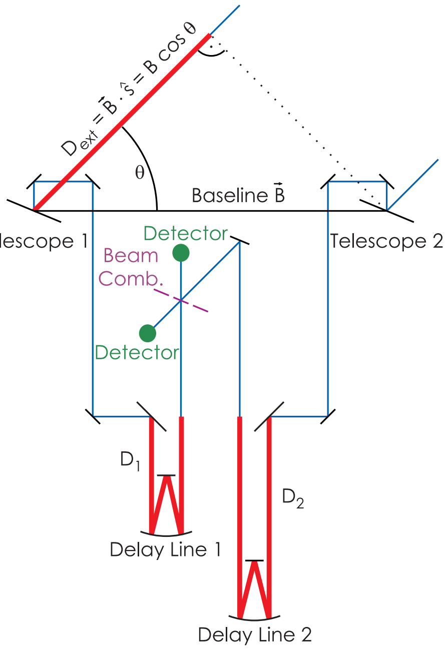

Figure 1. Schematic drawing of the light path through a two-element interferometer. The beam combiner is a 50% transmissive mirror. The external delay $D = \vec{B} \cdot \hat{s}$ is compensated by the two delay lines. The pathlengths D_1, D_2 through the delay lines are monitored with internal laser interferometers. The zero-order interference maximum occurs when the delay line positions are such that the internal delay $D_{\rm int} = D_2 - D_1$ is equal to D.

where $\hat{s}$ is a unit vector in the direction towards the star, and θ the angle between $\vec{B}$ and $\hat{s}$. Each data point is thus a one-dimensional measurement of the position of the star θ. The second coordinate can be measured with a separate baseline at a roughly orthogonal orientation.

To reduce errors due to atmospheric seeing and instrumental imperfections, one can perform simultaneous observations of two stars located close to each other on the sky. If the angle θ between these stars is sufficiently small, it can be shown that the contribution of atmospheric turbulence to the variance σ_θ^2 of measurements of θ scales with $\sigma_\theta \propto \theta$ and $\sigma_\theta \propto B^{-2/3}$ (Shao & Colavita 1992). For a good site such as Mauna Kea or Cerro Paranal astrometric measurements with a precision of $\sim 10\,\mu$ as are thus possible over angles of $\sim 10''$.

In a such a dual-star interferometer, each telescope accepts two small fields (of order a couple of arcseconds) and sends two separate beams through the delay lines. The delay difference between the two fields is taken out with an additional short-stroke differential delay line; an internal laser metrology system is used to monitor the delay difference. For astrometric observations, this delay difference ΔD is the observable of interest, because it is directly related to the coordinate difference between the target and reference stars; from Equation 1 it follows immediately that

$$\Delta D \equiv D_t - D_r = \vec{B} \cdot (\hat{s}_t - \hat{s}_r) = B(\cos\theta_t - \cos\theta_r), \tag{2}$$

where the subscript t is used for the target, and r for the reference.

The photon noise limit for the precision σ of an astrometric measurement is given by

$$\sigma = \frac{1}{\rm SNR} \cdot \frac{\lambda}{2\pi B}. \tag{3}$$

Since high signal-to-noise ratios can be obtained for bright stars, σ can be orders of magnitude smaller than the resolution λ/B of the interferometer. With an SNR $\sim$50, it is thus possible to attain a photon noise contribution to the astrometric error of $\sim$10 μ as on the longest baselines of the VLTI.

3. PRIMA AT THE VLTI

The PRIMA (Phase-Referenced Imaging and Microarcsecond Astrometry, Quirrenbach et al. 1998, Delplancke et al. 2000) facility will implement a dual-star capability at the European Southern Observatory's Very Large Telescope Interferometer (VLTI). The purpose of PRIMA is threefold:

- Provide on-axis and off-axis (within the isoplanatic angle) fringe tracking for all VLTI instruments;
- Conduct precise differential astrometry between stars separated by a few tens of arcseconds;
- Perform phase-referenced imaging of faint sources with off-axis fringe tracking.

The present infrastructure of the VLTI consists of the four 8.2 m "Unit Telescopes" of the VLT, four additional moveable 1.8 m "Auxiliary Telescopes" (ATs), six long-stroke delay lines (each one with two ports for dual-star operation), beam relay optics, and two focal plane instruments (MIDI and AMBER). The PRIMA hardware consists of four additional major sub-systems:

- Star separator systems (sometimes also called "dual star modules") that accept the light from two stars within a 2′ field and transfer it to the two input ports of the long-stroke delay lines;
- Differential delay lines (DDLs) that compensate the delay difference of up to a few cm between the two stars;
- Dedicated fringe detection units for the two stars;
- An end-to-end metrology system that monitors the internal differential delay with high precision.

The first, third, and fourth items from this list have been produced by various suppliers under contracts with ESO. The ESPRI consortium has produced the differential delay lines (Pepe et al. 2008), works together with ESO on the analysis of the astrometric error budget and on the development of the observing strategy, and will deliver software tools required to reduce astrometric data (Elias et al. 2008).

Each DDL consists of a monolithic cat's eye structure mounted on top of a translation stage that can move the cat's eye mirrors in the longitudinal direction over a distance of 70 mm. Parallel beam sliders with blade spring hinges ensure that a very high accuracy in the lateral directions is maintained. A two-actuator system is chosen; one to provide a long stroke, requiring a very accurate translation mechanism, and one actuator for the high frequency response over small displacements. The whole system is mounted in a vacuum system to have the differential OPD independent of environmental changes in refraction properties of the air. Each pair of delay lines is mounted in a separate vacuum vessel ($l \times w \times h = 1000\,\text{mm} \times 480\,\text{mm} \times 500\,\text{mm}$). A metrology system, based on a He-Ne laser (632 nm), measures the position of the translation stage via the same cat's eye, but along different paths to avoid interfering signals. The resolution of the metrology system is 1 nm. A local control electronics system is responsible for the control of the DDL; it also provides the interface between the DDL and the PRIMA control system.

4. ASTROMETRIC PLANET DETECTION

From simple geometry and Kepler's Laws it follows immediately that the astrometric signal θ of a planet with mass m_p orbiting a star with mass m_* at a distance d in a circular orbit of radius a is given by

$$\theta = \frac{m_p}{m_*}\frac{a}{d} = \left(\frac{G}{4\pi^2}\right)^{1/3} \frac{m_p}{m_*^{2/3}}\frac{P^{2/3}}{d}$$
$$= 3\,\mu\text{as} \cdot \frac{m_p}{M_\oplus} \cdot \left(\frac{m_*}{M_\odot}\right)^{-2/3} \left(\frac{P}{\text{yr}}\right)^{2/3} \left(\frac{d}{\text{pc}}\right)^{-1}. \quad (4)$$

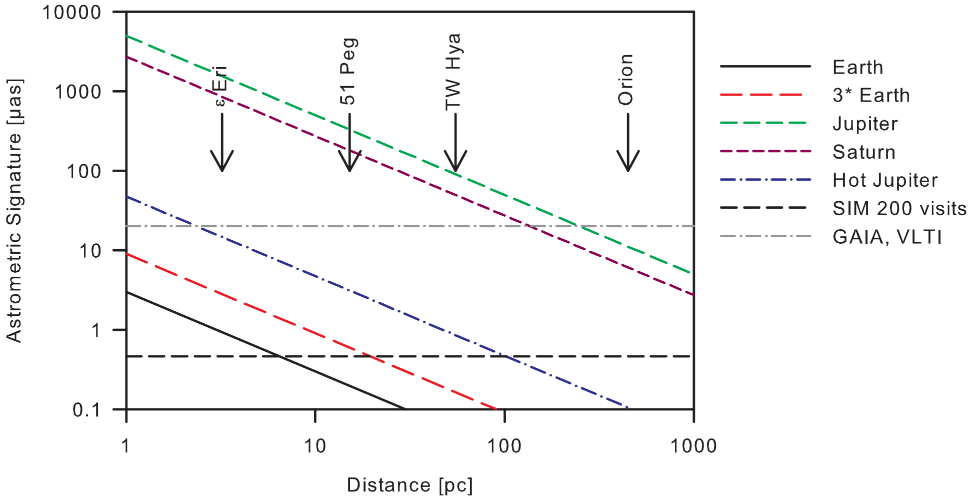

Figure 2. Astrometric signature (semi-amplitude) for five sample planets orbiting a Solar-mass star. Distances of a few benchmark objects are marked with arrows. Anticipated detection limits for ground-based (VLTI PRIMA) and space-based (Space Interferometry Mission) instruments are shown with horizontal lines. Adopted from Quirrenbach (2003).

This signature is shown in Figure 2 for five sample planets (analogues to Earth, a "heavy Earth", Jupiter, Saturn, and a "Hot Jupiter" with $m_p = 1\,M_{\rm jup}$ and $P = 4$ days) orbiting a $1\,M_\odot$ star. The detection bias of astrometry with orbital radius is opposite to that of the radial-velocity method, favoring planets at larger separations from their parent stars. Since the sensitivity of astrometry for a given type of planet drops linearly with d (unlike the radial-velocity technique), it is particularly important to select nearby stars for astrometric planet programs. With a precision of a few tens of microarcseconds per individual measurement, as expected for PRIMA and for the GAIA astrometric mission, it is possible to detect giant planets to distances of a few hundred pc. For the detection of terrestrial planets, a mission such as SIM pushing into the sub-microarcsecond regime will be needed (Unwin et al. 2008).

It should be pointed out that for circular orbits the observed astrometric signal is an ellipse with semi-major axis θ independent of the orbital inclination; the mass of the planet can therefore be derived directly from Equation 4 if the mass of the parent star is known. The situation is a bit more complicated for non-circular orbits, but even in that case the orbital inclination can be determined from the astrometric data with techniques analogous to those used for fitting orbits of visual binaries.

5. GOALS OF ESPRI

The ESPRI project (see also Quirrenbach et al. 2004 and Launhardt et al. 2008) will use the PRIMA facility to conduct a systematic survey of several categories of nearby stars: (1) stars that are already known to have planetary companions from radial velocity surveys, (2) the most nearby stars ($d \lesssim 15$ pc) of any spectral type, and (3) young stars with ages $\lesssim 300$ Myrs within $\sim$100 pc from the Sun. This survey will address the following questions:

- Resolve the $\sin i$ ambiguity of the mass for the already-known planets. This will improve the definition of the planet mass function, especially close to the upper end, where the statistics are poor.
- Determine the mutual inclination of planets in multiple systems. Many of the known extrasolar planets have highly eccentric orbits. A plausible origin of these eccentricities is strong gravitational interaction between two or several massive planets (Lin & Ida 1997, Papaloizou & Terquem 2001).

This could also lead to orbits that are not aligned with the equatorial plane of the star, and to non-coplanar orbits in multiple systems.

- Search for long-period planets around nearby stars of all spectral types. This will contribute to the characterization of planet properties (masses, orbital parameters) as a function of stellar mass, and thus provide constraints on competing theories of planet formation.
- Search for young planets, which could still be warm due to the heat trapped during their formation. These will be good targets for follow-up observations with the closure phase method (Joergens & Quirrenbach 2004), which could yield their spectra and thus shine light on the formation process and thermal history of giant planets.

ESPRI will thus make unique contributions to our knowledge of extrasolar planets, and pave the way towards a more precise astrometric survey with a space-borne interferometer, which could provide a census of terrestrial planets around nearby stars.

6. REFERENCE STARS AND PREPARATORY OBSERVATIONS

Since the targets for the ESPRI survey are rather bright stars ($K \lesssim 8$), they can be used to co-phase the interferometer. Consequently, long coherent integrations are possible for the astrometric references, which therefore can be much fainter; it is expected that stars down to $K = 13 \ldots 14$ should be suitable for PRIMA. Since the atmospheric contribution to the astrometric uncertainty as well as several important terms in the instrumental error budget are proportional to the separation between target and reference star, it is necessary to pre-select the target stars according to the presence of suitable astrometric references (Reffert et al. 2005, Geisler et al. 2008). Unfortunately, it is not possible to use catalogs based on existing all-sky surveys for this task, as they are either not sensitive enough, or contain many artifacts or "blind areas" around nearby stars.

We are therefore conducting a preparatory observing program using the SOFI near-infrared camera at the ESO 3.5 m New Technology Telescope on La Silla to obtain high-dynamic-range images of the fields of all potential ESPRI targets. The statistical expectation value of finding a star with $K \leq 14$ within $20''$ from a given star depends strongly on the Galactic latitude, ranging from $\sim$10% at high latitude to almost 100% near the Galactic plane. We find a somewhat larger number of stars in our fields, because many stars are members of wide physical pairs or multiple systems.

In those cases where only one reference star is available, an ambiguity may occur if an astrometric signal is detected, as only the relative motion between target and reference is measured. It may be impossible, for example, to distinguish the case of a target star with a planetary companion from that of a binary reference star. This is not a problem if the target is already known to host a planet, since then the period of the astrometric signal is known a priori, and interlopers due to duplicity of the reference become very unlikely. In addition, for many of the potential target stars, especially those at relatively low Galactic latitude, two or more good reference stars are available. These will be the preferred targets for the "blind" surveys, because in this case any astrometric signal can unambiguously be ascribed to one of the stars.

The information from our imaging survey, follow-up multi-color photometry and spectroscopy aimed at classifying the reference stars, and from catalogs (where available), is combined in a data base, which will be used for the final selection of the ESPRI target list, but will also be useful for the definition of other planet-search programs.

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