Scientific Results from High-precision Astrometry at the Palomar Testbed Interferometer

Matthew W. Muterspaugh\textsuperscript{a} Benjamin F. Lane\textsuperscript{b} Maciej Konacki\textsuperscript{c} B. F. Burke\textsuperscript{b} M. M. Colavita\textsuperscript{d} S. R. Kulkarni\textsuperscript{e} M. Shao\textsuperscript{d}

\textsuperscript{a}Department of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125;
\textsuperscript{b}Massachusetts Institute of Technology, Kavli Institute for Astrophysics and Space Research, Department of Physics, 70 Vassar Street, Cambridge, MA 02139;
\textsuperscript{c}Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences, Rabianska 8, 87-100 Torun, Poland;
\textsuperscript{d}Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., Pasadena, CA 91109;
\textsuperscript{e}Division of Physics, Mathematics and Astronomy, 105-24, California Institute of Technology, Pasadena, CA 91125

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ABSTRACT

A new observing mode for the Palomar Testbed Interferometer was developed in 2002-2003 which enables differential astrometry at the level of 20 micro-arcseconds (\(\mu\text{as}\)) for binary systems with separations of several hundred milli-arcseconds (mas). This phase-referenced mode is the basis of the Palomar High-precision Astrometric Search for Exoplanet Systems (PHASES), a search for giant planets orbiting either the primary or secondary star in fifty binary systems. We present the first science results from the PHASES search. The properties of the stars comprising binary systems are determined to high precision. The mutual inclinations of several hierarchical triple star systems have been determined. We will present upper limits constraining the existence of giant planets in a few of the target systems.

Keywords: Optical Interferometry, Phase-referencing, astrometry, PTI, binary star

1. INTRODUCTION

The Palomar High-precision Astrometric Search for Exoplanet Systems (PHASES) uses phase-referencing techniques to perform differential astrometry of sub-arcsecond binaries at the level of 20 \(\mu\text{as}\). These observations provide precision visual orbits of the binaries and allow detection of tertiary components orbiting either the primary or secondary due to the reflex motion of the subsystem center-of-light. A detailed description of the observational method and data analysis procedures was presented by Lane & Muterspaugh.\textsuperscript{1}

PHASES data are collected at the Palomar Testbed Interferometer (PTI),\textsuperscript{2} located on Palomar Mountain near San Diego, CA. It was developed by the Jet Propulsion Laboratory, California Institute of Technology for NASA, as a testbed for interferometric techniques applicable to the Keck Interferometer and other missions such as the Space Interferometry Mission (SIM). It operates in the J (1.2\(\mu\text{m}\)), H (1.6\(\mu\text{m}\)), and K (2.2\(\mu\text{m}\)) bands, and

\begin{flushleft}
Send correspondence to M.W.M.
M.W.M.: E-mail: matthew1@ssl.berkeley.edu, Telephone: 1 617 452 2304
\end{flushleft}
combines starlight from two out of three available 40-cm apertures. The apertures form a triangle with one 110 and two 87 meter baselines.

The primary goal of the PHASES program is to find and characterize giant planets in close binary systems. The existence of such systems poses strong challenges for models of giant planet formation. While it is possible each of the two processes currently favored—core accretion and gravitational instability—contribute to giant planet formation around single stars and wide binaries, simulations show both schemes have obstacles when a second star orbits so closely that it interacts with the planet-forming circumstellar disk, truncating it in size and heating it. In four exoplanet hosting binaries—HD 188753, γ Cephei, GJ 86, and HD 41004—the secondary star would have truncated the disks to less than 6 AU. It is possible that some of these systems reached their current configurations via dynamical interactions in the short-lived star clusters in which they formed, though this post-formation mechanism appears too infrequent to explain the number found. These systems have been identified with the radial velocity (RV) method. PHASES employs astrometry, from which the companion mass can be identified without the ambiguity of the orbital inclination. Furthermore, the relative orientations of the binary and planetary orbits can be determined in order that system dynamics can be studied. This effort and others specifically targeting close binaries will better determine the frequency of planets in binaries; if large, this will be strong motivation for a revolution in the theory of giant planet formation.

2. METHOD

The challenge of astrometric detections of planets in binaries comes from the small size of the reflex motions they cause to the host stars. Giant planets mass a factor of 1000 less than stars, and are only stable in orbits sized of order 1/10 of the binary separation or smaller. Thus, one requires an astrometric precision of order $10^{-4}$ of the binary separation. This goal drives one to use high spatial resolution techniques.

An optical interferometer coherently combines light from two or more telescopes to measure the resulting sinusoidal intensity variations that result from constructive and destructive interference of the starlight. These “fringes” form the basic observable for interferometric imaging. Constructive combination requires that the total optical paths from a star through each of the telescopes are matched to identical wavefront phases. The optical bandpass creates an envelope function modulating the fringe contrast, resulting in an observable fringe packet. For systems with finite optical bandpasses, fringes with large contrast form only within a limited range of differential optical paths, centered at a zero value where the optical pathlengths are identical for the interferometer arms being combined.

The optical path lengths traversed by the starlight have several terms. First, variations in atmospheric indices of refraction over each telescope can introduce time-variable differential path terms. Second, if a target is not directly overhead, one telescope will be slightly closer than the other, introducing a geometric term $\vec{B} \cdot \vec{s}$ where $\vec{B}$ is the baseline vector connecting two telescopes, and $\vec{s}$ is the unit vector in the direction of the star. Finally, path variations internal to the interferometer must be included; in practice, these internal paths are actively varied to compensate for the first two terms.

Note that the geometric term $\vec{B} \cdot \vec{s}$ varies with sky position. A binary star will produce two fringe packets centered at slightly different delays. For PHASES targets, the packets do not overlap, see figure 1. If their separations are small, the atmospheric contribution to the differential path length is correlated spatially. Thus, measuring the differences in internal delays required to produce each fringe packet determines the binary separation projected along the baseline vector.

While the atmospheric terms are correlated spatially, they vary in time. These variations must be monitored if the fringe packets are measured at different times. The monitoring and correcting of these fluctuations are known as “phase-referencing”. PTI’s original phase-referencing mode operated on two sources separately resolvable by the interferometer telescopes. This is modified to a simpler version that studies all components within one telescope resolution element. Two interferometric beam combiners are used: one tracks just a single fringe of any star in the one-arcsecond field and operates on fast (10 ms) timescales to monitor the atmosphere, the other one makes precise measurements of the relative positions of each star in the atmosphere-stabilized field. This latter system samples both fringe packets by introducing a triangle-wave internal path modulation with amplitude $\sim 100–300\mu m$ and period $\sim 1–3$ seconds. Several thousand scans through the double interferograms
are recorded in an hour of observation. In post-processing the optical path separation of the binaries is converted to projected sky separation via an algorithm that depends on the baseline of the interferometer and sky position of the target.

Night-to-night repeatability at the $\sim 20\mu\text{as}$ level has been demonstrated for many target systems with binary separations of order $\sim 200\ \text{mas}$. This matches the $10^{-4}$ relative precision needed to detect giant planets.

### 3. LIMITS ON TERTIARY COMPANIONS

PHASES observations of several binaries span 2-3 years. It is now possible to search for perturbations to the Keplerian orbits that would indicate the presence of tertiary companions, and determine the mass threshold above which companions can be shown not to exist. This mass threshold depends on the companion orbital period and these two parameters form a phase-space over which one can search for orbital configurations that are consistent with the observations. This search is computationally intensive and is currently limited to face-on, circular orbits.

#### 3.1. $\delta$ Equulei

The combined visual and RV orbit of $\delta$ Equulei (7 Equ, HR 8123, HD 202275) was described by Muterspaugh et al.\textsuperscript{13} That study was able to determine the component masses at the 1% level and the distance to the system at a precision of 0.05 pc; improvement on these quantities will require additional RV observations. In the 2005 observing season, an additional 11 PHASES measurements have been made, bringing the total to 38. The new visual orbit is shown in figure 2 with the PHASES observations.

Figure 3 shows the regions in companion mass-period phase space for which the measurements are inconsistent with a perturbation caused by a hypothetical faint companion in a face-on circular orbit. Companions with
masses greater than the line plotted are inconsistent with the PHASES observations; the excluded regions are those above the lines. Also shown are the exclusion regions for 170 differential astrometry measurements made by visual micrometry and speckle interferometry. The stability criteria of Holman & Wiegert indicates that planetary companions are stable only in orbits of 2/3 year or less.

3.2. 13 Pegasi

Twenty-five PHASES measurements have been made of 13 Pegasi (HR 8344, HD 207652). Massive planets in 20 day to 3 year period face-on circular orbits would perturb this binary by more than the observed scatter in the PHASES data. Planets as small as two Jupiter masses are ruled out in ∼ 4 month period orbits.

4. TRIPLE STAR SYSTEMS

Studies of binary systems combining visual and RV orbits are able to measure component masses and the distance to the system (without relying on parallax observations), quantities that cannot be extracted from observations using only one method or the other. A star’s mass is the most important property determining its evolution. Measuring the distances to binaries can be a crucial step in establishing astrophysical distance scales, as in the case of the Pleiades.

Until recently the number of binary systems for which such combined visual and RV orbits were possible was severely limited by the conflicting observational biases for visual and RV measurements; visual orbits are more easily measured for long-period, widely separated systems, whereas velocities are largest in short-period systems. The gap between visual and RV measurements has been bridged by the maturation of long baseline optical interferometry, which has been used to obtain high resolution measurements of the visual orbits of spectroscopic binaries.

The problem is compounded for hierarchical triple star systems (in which one component of the “wide” binary is itself a much shorter period “narrow” binary). In order that the RV amplitude of the wide pair is large enough to be detected, its orbital period must be equally short (and have corresponding separation as small) as the two-component binaries in combined RV/visual studies. As the “narrow” pair is necessarily smaller (by a
Figure 3. The Mass-Period phase-space for tertiary companions that can be excluded by PHASES observations of two binary star systems. On the left, 1– (solid line) and 3–σ (dashed line) χ^2 contours for δ Equulei are shown; the corresponding contours based solely on micrometer and speckle interferometry data are also shown. On the right, the same contours for 13 Pegasi, based only on PHASES measurements. Note that a range of giant planets in face-on orbits are ruled out by the PHASES observations.

To study the mutual inclination of the orbits in such a system, both RV and visual orbits for both wide and narrow systems in a triple are required. Thus, determinations of the mutual inclinations of the two orbits in hierarchical triple stellar systems are rare, with only four previous systems having been studied. Mutual inclination measurements are useful in studying properties of the environments in which stars form; the dynamical relaxation process undergone by multiples after formation is expected to leave a statistical “fingerprint” in the distribution of mutual inclinations.\textsuperscript{19} This provides motivation to overcome the challenge that extending the RV/visual overlap presents. PHASES differential astrometry operating on subarcsecond binaries with a relative precision of 10^{-4} can identify the center-of-light perturbation due to the Keplerian orbit of a subsystem in one of the two components.

κ Pegasi is a well-known, nearby triple star system. It consists of a “wide” pair with semi-major axis 235 mas, one component of which is a single-line spectroscopic binary (semi-major axis 2.5 mas); see figure 4. Using PHASES differential astrometry and iodine-cell referenced radial velocity observations, the masses for all three components are determined and the relative inclination between the wide and narrow pairs’ orbits is found to be 43.8 ± 3.0 degrees, just over the threshold for the three body Kozai resonance.\textsuperscript{20} The system distance is determined to 34.64 ± 0.22 parsec, and is consistent with trigonometric parallax measurements. The PHASES observations show conclusively that a previously suggested additional (fourth) stellar component is not present in the system. Future investigations of this system to determine the relative luminosities of the three components will allow model fitting of the components’ evolutions, of particular interest because two components have evolved slightly off the main sequence.

Using PHASES observations, a similar study was made of the V819 Herculis system\textsuperscript{21} (HR 6469, HD 157482). The mutual inclination is found to be 23.6 ± 4.9 degrees. It should be noted that the center-of-light wobble of the V819 Her narrow pair is ∼ 110μas; this same amplitude would identify a planetary companion if the pair’s orbital period were several months instead of two days. These two triples represent just the fifth and sixth
unambiguous determinations of the mutual inclinations of the orbits in hierarchical triple star systems. The distributions of the six known systems disagree (at the 96% level) with what one would expect from random orientations, suggesting structure in the angular momentum distributions of star forming regions; see figure 5.

Figure 4. The visual orbits of κ Pegasi (left) and V819 Herculis (right) showing perturbations by third components.

Figure 5. Cumulative distribution of the six systems with unambiguous mutual inclinations (set 6U). The set ST is that of Sterzik & Tokovinin, who included both possible mutual inclination angles for each of 22 systems for which only ambiguous values were possible. By including both possible angles, distribution ST may be “diluted” and partially biased towards randomly oriented orbits. The theoretical distribution for random orientations is also shown. The difference between 6U and random is statistically significant at the 96% level.

5. CONCLUSIONS

The PHASES program at PTI has been making routine observations for 2-3 years with relative astrometric precisions at the $10^{-4}$ level. The first results have been high precision orbits of binary and triple systems, including measurements determining the mutual inclinations of the wide and narrow pairs of two triples. Observations are starting to rule out the existence of planet-mass companions in several systems, and will be able to detect giant
planets in longer period orbits as the search continues over the next years. Detecting planetary companions in these close binaries will challenge current models of planet formation, and the astrometric nature of the observations will present uniquely detailed information on the companions, including mass without inclination ambiguities.

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