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Matthew W. Muterspaugh, Benjamin F. Lane, Bernard F. Burke, Maciej Konacki, Shri R. Kulkarni, "Initial scientific results from phase-referenced astrometry of sub-arcsecond binaries," Proc. SPIE 5491, New Frontiers in Stellar Interferometry, (20 October 2004); doi: 10.1117/12.551980

Event: SPIE Astronomical Telescopes + Instrumentation, 2004, Glasgow, United Kingdom

Initial Scientific Results from Phase-Referenced Astrometry of Sub-Arcsecond Binaries

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ABSTRACT

The Palomar Testbed Interferometer has observed several binary star systems whose separations fall between the interferometric coherence length (a few hundredths of an arcsecond) and the typical atmospheric seeing limit of one arcsecond. Using phase-referencing techniques we measure the relative separations of the systems to precisions of a few tens of micro-arcseconds. We present the first scientific results of these observations, including the astrometric detection of the faint third stellar component of the κ Pegasi system.

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

1. INTRODUCTION

A new method of ground-based differential astrometry with measurement precisions on the order of 10^{-5} arcseconds for bright stars separated by $\approx 0.05 - 1.0$ arcseconds has been developed for use at the Palomar Testbed Interferometer.[1] Observations using this method have been carried out over the past year on 25 binary systems as part of the Palomar High-precision AStrometric Exoplanet Search (PHASES). PHASES will monitor up to 50 such systems over ≈ 3 years for a number of scientific purposes, including a search for astrometric perturbations caused by faint (planetary) companions orbiting one of the main stars of a system ("S-type orbits," as opposed to "P-Type" companions which orbit both stars).

One system in the PHASES study is κ Pegasi (HR 8315, HD 206901). This system is comprised of two F5 subgiant stars (here referred to as A and B; for historical reasons, B is the brighter and more massive—this distinction has been the cause of much confusion) and a faint stellar companion orbiting B (which this paper designates as "b"). An additional component C is well separated from the other members of the system (13.8 arcseconds) and is faint; this may be optical and is not relevant to the present analysis. Using the best available values for the masses of stars A and B, combined with the most recent elements of the A-B visual orbit,[2] the stability criteria of Holman and Wiegert[3] for S-type companions predicts that objects with orbital periods as long as five months are stable in this system. Both A and B have been reported as suspected spectroscopic subsystems (here referred to as A-a and B-b, respectively), but no companion to A has been confirmed.

Burnham discovered the sub-arcsecond A-B binary in 1880.[4] Since this discovery, an number of studies have been carried out to determine the orbit of A-B and to search for additional components. In 1900 Campbell &

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New Frontiers in Stellar Interferometry, edited by Wesley A. Traub,
Proceedings of SPIE Vol. 5491 (SPIE, Bellingham, WA, 2004)
0277-786X/04/$15 · doi: 10.1117/12.551980

Wright[5] reported a period and semimajor axis for the A-B pair of 11 years and 0.4 arcseconds, respectively, and that the brighter of the stars is a spectroscopic binary with a period "that seems to be about six days." Luyten[6] combined all previous observational data to produce a visual orbit between components A and B and a spectroscopic orbit for the 5.97 day B-b system (he interchanged the designations A and B; here we have converted his results to the convention previously mentioned). His work also discredited previous claims that the line of apsides of B-b varied with the period of the A-B system. Luyten derived a mass for component A of 1.9 $M_\odot$ and a combined mass for the B-b subsystem of 3.3 $M_\odot$. Additionally, because there are no observed eclipses in the B-b system, he concluded that the maximum possible mass ratio M_B:M_b is 3:1. Beardsley & King[7] obtained separate spectra for components A and B. Their observations confirmed that component B is a 5.97 day single-line spectroscopic binary, and also suggested that A was a spectroscopic binary with period 4.77 days. Mayor & Mazeh[8] have published the most recent spectroscopic orbit for the B-b subsystem, as well as several measurements of the radial velocity of component A, which did not confirm the proposed 4.77 day companion a. Mayor & Mazeh appear to switch naming conventions for components A and B several times in their paper. They report a mass ratio "M_A:$M_B = 1.94 \pm 0.6$"; this is counter to the tradition of κ Pegasi B being the more massive star, and the correct value is probably the inverse of this. Mayor & Mazeh indicate that it is component B that contains the 5.97 day spectroscopic binary. The most recent visual orbit for system A-Bb was published by Söderhjelm using historical data combined with Hipparcos astrometry.[2] Because the period is short and Hipparcos was capable of wide-field astrometry, estimates for the parallax (27.24 ± 0.74 mas), total mass (4.90 $M_\odot$), and mass ratio of components A and B (M_B:$M_A = 1.76 \pm 0.11$, in inverse agreement with Mayor & Mazeh) were also possible. This paper reports astrometric PHASES data that detects the reflex motion of the center-of-light of the B-b subsystem relative to the primary star A, with a period of 5.97 days.

Observations were made using the Palomar Testbed Interferometer (PTI).[9] PTI is located on Palomar Mountain near San Diego, CA. It was developed by the Jet Propulsion Laboratory and 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 (1.2μm), H (1.6μm), and K (2.2μm) bands, and combines starlight from two out of three available 40-cm apertures. The apertures form a triangle with 86 and 110 meter baselines. The differential astrometry mode used by the PHASES project has been demonstrated using K band light from the North-South (110 meter) and the South-West (86 meter) baselines; the North-West (86 meter) baseline will become operational for this mode this year. All data presented in the current paper were taken using the North-South (longest) baseline.

2. OBSERVATIONAL SETUP AND DATA REDUCTION PROCESS

The observational setup used is described in detail in Lane & Muterspaugh 2004.[1] The technique is built upon the fact that, in an interferometer, the position of zero total optical path delay (the point at which broadband light interferes with maximum intensity) depends on the direction to the light source. By measuring the relative zero-delay locations of stars, one can determine their relative sky positions. If the stars are separated by a small angle on the sky, atmospheric contributions to the optical delay are common and cancel. The atmospheric terms in the optical delay are not constant in time; in the absence of making simultaneous measurements of all stars, one must be able to monitor and correct for changes in the atmospheric optical delay. We make this correction using a technique known as phase-referencing.

Each of two telescopes collects light from all stars in a target field of approximately 1 arcsecond. The light is then passed through low-vacuum pipes to an optical lab where movable mirrors (delay lines) introduce optical delays to compensate for the geometric delays associated with an interferometer. The light from all stars go through a common path through the delay lines; no significant amount of differential delay is added to the light of various stars in the field through this process. The light from each telescope is then split using beamsplitters. A portion of this light (roughly 70%) from each telescope is combined to produce an interference pattern on a high-speed (10-ms) fringe-tracking detector. This actively monitors the fringe position of one star in the field to determine the delay motion added by the atmosphere. This measurement is fed back to the optical system to remove a portion of the temporal effects of the atmosphere.

The rest of the starlight (30%) is combined separately. This "science" combiner is able to take measurements over much longer time periods because it is phase-referenced to the fringe-tracking combiner, which removes much of the atmospheric delay variability. For this experiment, we choose to scan in delay with relatively large amplitude (on order 100 wavelengths, or 220 microns) so as to measure the interferograms at the locations of each star in the system. The scanning is done in a triangle waveform with periods on the order of 2-3 seconds. A laser metrology system is used to measure the differential path length between the fringe-tracking and science beam combiners.

The data reduction process was similar to that described in Lane & Muterspaugh, 2004. The science-combiner data is broken into "scans" each time the scanning delay direction changes. A likelihood function of the projected delay separation is determined on a scan-by-scan basis by creating a model double fringe packet for all possible delay separations and evaluating χ^2 for each at all possible delay positions; χ^2 is used as the figure of merit to construct the likelihood function. Because there are multiple fringes in each star's interferogram, this likelihood function has many local maxima and minima separated by the fringe spacing. For a typical target, the signal-to-noise ratio in a single scan is not large enough to determine the correct global maxima, resulting in a periodic ambiguity in the projected separation. The likelihood function is remapped into a grid of differential declination and differential right ascension. The likelihood functions for all scans (typically 500-3000 scans per target per night) are coadded in this grid, improving the SNR enough to determine the sky separation of the two stars observed unambiguously. A direct fit of a rotated two-dimensional quadratic to the coadded likelihood function determines the formal uncertainties of the astrometric measurement. The two-dimensional likelihood function itself is used to plot error ellipses.

The data analysis presented in this paper does not include the effects of aberration, precession, nutation, or parallax. These astrometric corrections are predicted to affect the results in two ways. The most obvious effect is that the apparent global astrometry for the system as a whole will be different than that used. An error of 1 arcsecond in mean global system astrometry introduces an error in the measured separation of 10^{-6} arcseconds. These astrometric corrections can be as large as a few tens of arcseconds, resulting in differential astrometry errors of magnitude similar to our observed precisions (10^{-5} arcseconds). A second effect is due to a variation in true North with time. This will introduce errors in measured position angles. Because the observations presented were carried out over a timescale of a few months and these effects are slowly varying, the precision of the data and observational repeatability will not be affected in any significant manner, nor will the precisions with which orbital elements are able to be determined from the data. To determine orbital elements with accuracies equal to the observed measurement precision will require including these astrometric terms; to the extent that these effects are significant, all orbits presented in this paper are preliminary. However, the size of the reflex motion of κ Pegasi B by the unseen companion b is an order of magnitude larger than the expected effect any of these corrections will have on the differential astrometry measurements. We are working to include these astrometric corrections for future analysis.

3. OBSERVATIONAL PERFORMANCE

PHASES has observed 25 binary systems each multiple times. The data from a number of these has been reduced and analyzed to determine observational repeatability. See "Phase Referencing and Narrow-Angle Astrometry in Current and Future Interferometers," by Lane & Muterspaugh in this proceedings, for more details.

Most of the κ Pegasi data presented in this paper was taken during the 2003 observing season. Over a similar time range the long-period (order century) systems HR 6983 (HD 171779) and 72 Pegasi (HR 8943, HD 221673) were observed in the same mode, each with over 20 nights of observations. For both systems the formal uncertainty error ellipses were typically 5×100 μas (1 μas $= 10^{-6}$ arcseconds); for a few data points taken over a wide range of hour angles, the major axis uncertainties were nearly equal to those of the minor axis. The orbital motions of these long period systems are well described by linear or polynomial models; a fit of this type establishes our night-to-night repeatability. For HR 6983, the reduced $\sqrt{\chi_r^2} = 4.7$, and a similar factor is found for 72 Pegasi. Separate fits to the one-dimensional uncertainties in the δR.A. or δDec axis produce similar values, indicating that the scale factor between formal and actual errors is uniform. Our demonstrated night-to-night repeatability is 24 μas for these systems.

To reduce this scaling factor, we have added a laser metrology system to a short amount of differential starlight path that had previously been unmonitored; this improved system is in use for the 2004 observing season. Initial repeatability measurements on the star β CrB (HR 5747, HD 137909) indicate that this scale factor has been reduced to approximately 2.6. A direct comparison using the same targets must wait until summer 2004, when HR 6983 and 72 Pegasi are again observable.

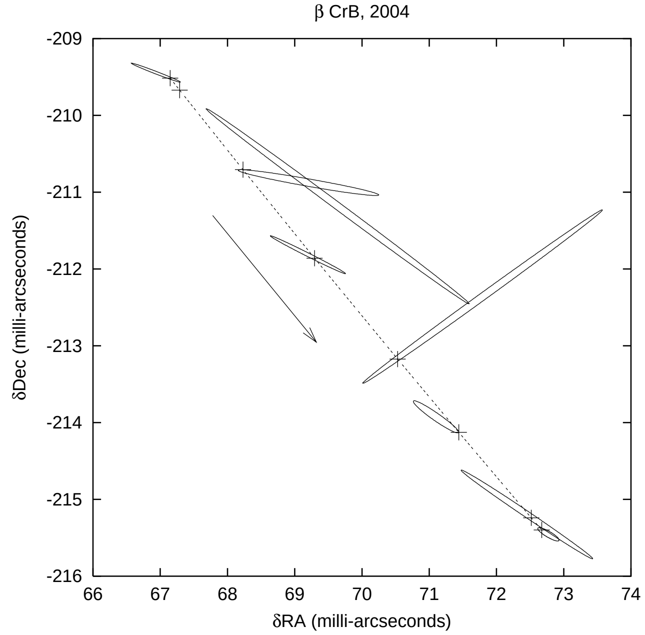

Figure 1. Observed repeatability of the differential astrometry of β CrB during the 2004 observing season. Error ellipses have been rescaled by the appropriate factor (2.6). Arrow indicates direction and rate of motion, with length 10 days.

The appropriate scaling factor has been applied to the formal uncertainties of κ Pegasi data presented in this paper; the correction has been applied to the error bars and ellipses plotted in all figures. Due to the orientation of the baseline with the binary's separation angle, the target was typically observable for much less than an hour each night. We find the average scaled minor-axis uncertainty for κ Pegasi is 45 μas, and that for the major axis is 1.5 mas. This extreme axis-ratio is to be expected from a single baseline interferometer. It should be noted, however, that 9 data points have scaled minor-axis uncertainties of less than 30 μas and 8 have scaled major-axis uncertainties of less than 250 μas. All data points have scaled minor-axis uncertainties less than 1/8 of the observed semi-major axis of the orbit of the B-b center-of-light.

4. ASTROMETRIC MODEL

We have applied basic models to our astrometric data. We make the simplifying assumption that the B-b subsystem is unperturbed by star A over the timescale of our observing program, allowing the model to be split into a wide (slow) interaction between star A and the center of mass of Bb, and the close (fast) interaction between stars B and b. The preliminary results presented in this paper result from modeling both the A-Bb and B-b motions with Keplerian orbits. Because our data were taken over a time short compared to the period of the A-Bb system, the period and eccentricity of the wide system were held fixed at the values determined by Söderhjelm.

In general, one cannot simply superimpose the results of the two orbits. The observable in our measurements is the separation of star A and the center-of-light of the B-b subsystem. Because the center-of-light of B-b, the center-of-mass of B-b, and the location of star B are generally all unequal, a coupling amplitude must be added to the combined model. This coupling amplitude measures the relative size of the semi-major axis of the B-b subsystem to that of the motion of the center-of-light of the B-b subsystem. The sign of the superposition is determined by the relative sizes of the mass and luminosity ratios of the stars B and b. As an example, if the center-of-light is located between the center-of-mass of B-b and the location of star B, the motion of the center-of-light will be in opposite direction to the vector pointing from B to b. For a subsystem with mass ratio $M_{\mathrm{b}}/M_{\mathrm{B}}$ and luminosity ratio $L_{\mathrm{b}}/L_{\mathrm{B}}$, the observed quantity is

$$\overrightarrow{y_{\mathrm{obs}}} = \overrightarrow{r_{\mathrm{A-Bb}}} - \frac{M_{\mathrm{b}}/M_{\mathrm{B}} - L_{\mathrm{b}}/L_{\mathrm{B}}}{(1+M_{\mathrm{b}}/M_{\mathrm{B}})\,(1+L_{\mathrm{b}}/L_{\mathrm{B}})}\overrightarrow{r_{\mathrm{B-b}}}$$

where $\overrightarrow{r_{\mathrm{A-Bb}}}$ is the model separation pointing from star A to the center-of-mass of Bb, and $\overrightarrow{r_{B-b}}$ is the model separation pointing from star B to star b. Including this coupling term for astrometric data is important when a full analysis including radial velocity data is made.

Alternatively, one can directly combine a model of the A-Bb system with a model of the motion of the center-of-light of B-b. For purely astrometric data such a model is appropriate. In this case, there is no sign change for the B-b center-of-light model, and no extra coupling amplitude is required. This was the model used to construct preliminary orbits for the current paper.

$$\overrightarrow{y_{\mathrm{obs}}} = \overrightarrow{r_{\mathrm{A-Bb}}} + \overrightarrow{r_{\mathrm{Bb,C.O.L.}}}$$

Radial velocity data are available for κ Pegasi A and B (e.g. Mayor & Mazeh 1987). An effort to incorporate these data in a full three-dimensional double-orbit model is currently under way.

5. ANALYSIS AND DISCUSSION

The data was simultaneously fit to two Keplerian models; one representing the A-Bb interaction, and another representing the motion of the center-of-light of the B-b subsystem. The period and eccentricity of the wide system were fixed at Söderhjelm's values of 4233 days and 0.31, respectively; our few months of observation do not allow these parameters to be well-determined. All elements of the preliminary A-Bb orbit agree well with both Luyten's and Söderhjelm's results.

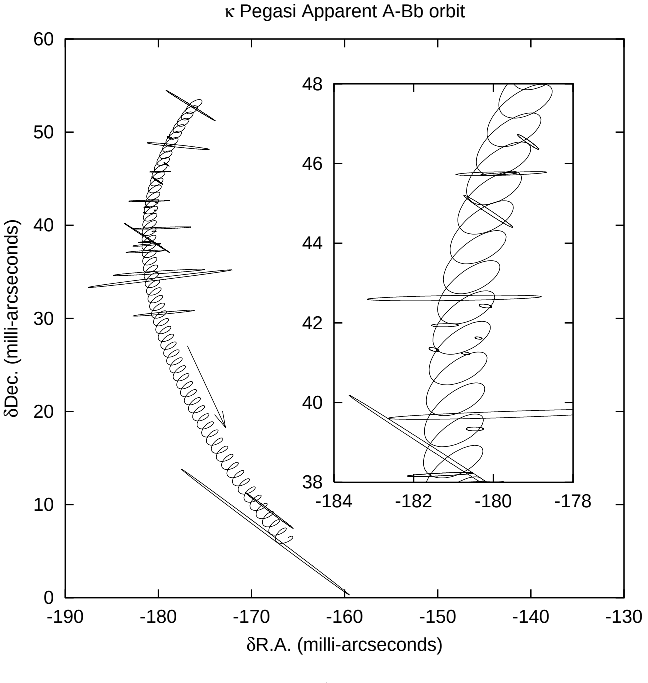

Figure 2. A preliminary apparent orbit between κ Pegasi A and the center-of-light of subsytem Bb, over the time period of PHASES data. Arrow indicates direction of increasing time, with a length of two months. Also plotted are the 1-σ error ellipses for PHASES data. The error ellipses are generally much longer in one dimension than the other because a single-baseline interferometer is more precise in measuring quantities parallel to the baseline vector.

PHASES data is particularly well-suited to determining the orbital elements of the B-b subsystem. Because the B-b subsystem has short period (our fit gives 5.9691 ± 0.0022 days), the system can be studied in a relatively short time. The apparent semi-major axis of the center-of-light of B-b is roughly 864 ± 27 μas, a factor roughly 20 times larger than our average precision; this large signal makes κ Pegasi Bb ideal for developing astrometric methods. A full model of the A-Bb orbit will require either several years of observation, or including historical micrometer or speckle interferometry data.

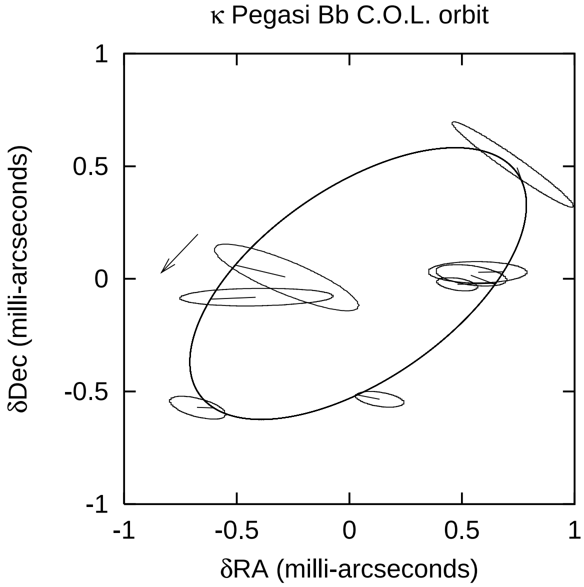

Figure 3. Preliminary orbit of the center-of-light of subsystem B-b, with the long-period A-Bb orbit removed. For clarity, only those data with both error ellipse axis smaller than the semi-major axis of the orbit have been plotted. Lines connect each data point to its corresponding point in the orbit. Arrow indicates orbital motion over 6 hours near periastron.

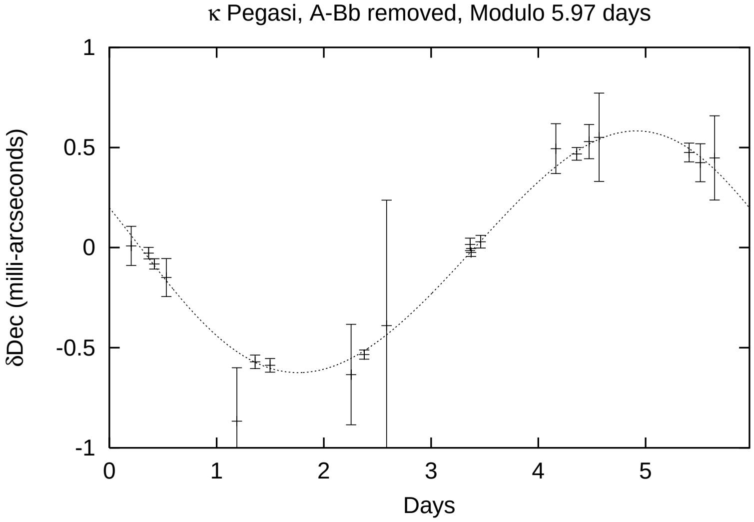

Figure 4. Residuals to the A-Bb model for κ Pegasi, in differential declination (typically our more sensitive dimension), wrapped about the period of B-b (5.9691 days). Also plotted is the preliminary Keplerian model of the motion of the center-of-light of B-b. For clarity, 6 data points with declination uncertainties larger than the semi-major axis motion of the center-of-light of B-b (864×10^{-6} arcseconds) have not been included in the plot.

The period of the preliminary astrometric B-b orbit agrees well with the previous spectroscopic results (5.9691 ± 0.0022 days versus 5.97164 ± 0.00006 from Mayor & Mazeh and 5.97152 ± 0.00002 from Luyten). Using our fit value for the B-b inclination of 119.7 ± 2.8, Mayor & Mazeh's value for $K_B = 42.1 \pm 0.3$ km/s, and the Hipparcos parallax, one calculates that the semi-major axis of component B itself is roughly 760 μas, a value *smaller* than that found for the astrometric motion. (This disagreement is most likely due to the preliminary nature of the analysis. However, it may be within the errors of parallax measure—Pan, Shao, & Kulkarni[10] demonstrated the Hipparcos distance to Atlas was in error by 10% or more; a similar error for κ Pegasi would result in the semi-major axis measurements agreeing within the errors.) The rough agreement of the two values suggests that the center-of-light of B-b is very close to the location of B itself. Making the approximation that star b is faint, the mass ratio is $M_b/M_B = 0.51$. Söderhjelm's value for the mass of subsystem B-b of $3.13 \pm 0.2 \mathrm{M}_\odot$ implies that component b has mass $1.05\mathrm{M}_\odot$. Stars A and B have apparent magnitudes $K \approx 3.8$ and $K \approx 3.6$. If b is a main-sequence star, it would have an apparent magnitude of approximately K=5.8, corresponding to a luminosity 7.5 times fainter than B. In the scope of this preliminary orbit, this is consistent with the proposition that the center-of-light of B-b is located near B. The sensitivity of PHASES to lower-mass companions improves for longer companion periods. While the current observations are only sensitive to objects of mass $0.1\mathrm{M}_\odot$ in 6-day orbits about κ Pegasi B, this drops to 6 Jupiter masses for companions with 5 month periods.

The mean orbital motion of the center-of-light of the B-b subsystem is roughly 900 μas per day. Superimposing the A-Bb orbit adds on average 340 μas of motion per day. During a typical one-hour observation, the total motion can be as large as 50 μas. The motion has little curvature over this time period, so the average differential astrometry measure can be taken as the value for the average time. Observations with higher precision will require modeling the motion within a single night's observing.

We see no evidence supporting a 4.77-day period companion to κ Pegasi A. The suggested amplitude for the velocity curve in Beardsley & King was roughly 30 km/s, corresponding to astrometric motion of star A on order 1.1 mas, an effect that would be seen in the PHASES astrometric data if present. The radial velocity measurement precision was of order 1 km/s; the current PHASES data set could detect companions at this same level, with masses as small as $0.05\mathrm{M}_\odot$ for a 4.77-day period (the PHASES uncertainty in $a_{Bb,C.O.L.}$ is 27 μas, 41 times smaller than the expected 1.1 mas effect and 1.4 times smaller than the astrometric perturbation of an object causing a 1 km/s reflex motion). For companions in longer periods, PHASES is more sensitive than these radial velocity observations. There is no evidence for any components other than A, B, and b at this time.

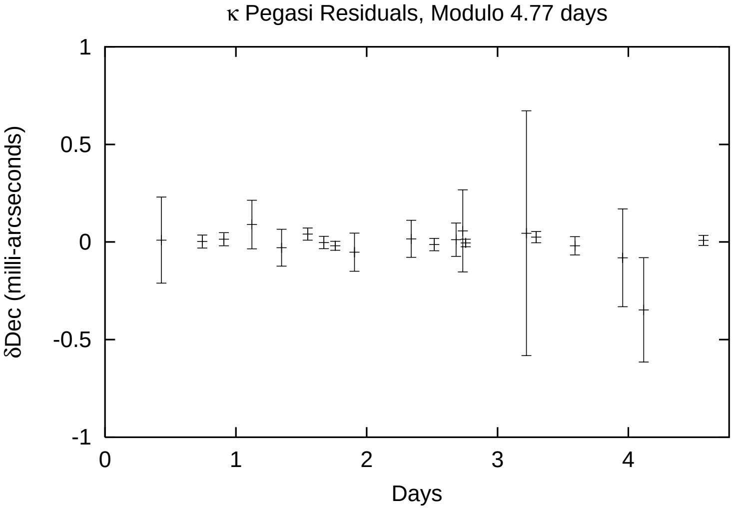

Figure 5. Residuals to the preliminary double-Keplerian model for κ Pegasi, in differential declination (typically our more sensitive dimension), wrapped about 4.77 days. There is no evidence supporting a 4.77 day companion to κ Pegasi A, as had been suggested by the radial velocity observations of Beardsley & King. For clarity, 6 data points with declination uncertainties larger than the semi-major axis of motion of the center-of-light of B-b (864×10^{-6} arcseconds) have not been included in the plot.

6. CONCLUSIONS

The high-precision separation measurements obtained in the PHASES survey of sub-arcsecond binaries detect the astrometric effect of the unseen companion b in the κ Pegasi system. The observed astrometric effect is nearly two orders of magnitude larger than the demonstrated measurement precision. The companion star is possibly a main-sequence star of type early G. The orbital parameters agree well with the established single-line spectroscopic orbit previously identified. There is no evidence to support the suggestion that κ Pegasi A has a 4.77 day companion; such a companion would be readily identified in the PHASES data.

Phase-referenced differential astrometry is useful for studying low-luminosity companions in S-type orbits to binary stars. This method will allow detection of planetary mass companions whose periods are longer than that of κ Pegasi b, in sub-arcsecond binaries, should they exist. Such longer-period companions are better suited for astrometric than radial velocity observations; even for companions in week-long periods our astrometric data rivals the sensitivity of previous studies of the κ Pegasi system. κ Pegasi is an ideal testbed for developing astrometric techniques.

ACKNOWLEDGMENTS

The PHASES project is funded by the Astronomy Department at the California Institute of Technology. We thank the members of the PTI Collaboration for their contributions to the instrument construction, operation, maintenance, and continued improvements. We would like to thank M. Colavita, K. Rykoski, and N. Safizadeh for their contributions to this effort. Interferometer data was obtained at the Palomar Observatory using the NASA Palomar Testbed Interferometer, supported by NASA contracts to the Jet Propulsion Laboratory. We thank the staff of Palomar Observatory. M.W.M. acknowledges the support of the Michelson Graduate Fellowship program. B.F.L. acknowledges support from a Pappalardo Fellowship in Physics.

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