Astrometry with the Keck Interferometer

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ABSTRACT

A key thrust of NASA's Origins program is the search for and detection of planetary systems about other stars. Pursuing this goal in a cost-effective and expedient manner from the ground has led NASA to begin work on the Keck Interferometer, which will add 4 1.8m 'outrigger' telescopes at the Keck Observatory on Mauna Kea. In addition to the imaging science to be performed by the Keck 10m telescopes with the outriggers, another one of the principal capabilities of the instrument will be the ability for the outriggers to conduct relative astrometry at the 25 microarcsecond level per root hour. Astrometry of this accuracy will enable the array to detect planetary systems composed of Uranus-mass or larger bodies orbiting at 5 AU solar mass stars at a distance of 20 pc; over 300 stars are to be surveyed by the outriggers annually. The astrometric capabilities of the Keck array can also be utilized other astrophysical investigations, such as characterization of spectroscopic binary orbits, and the measurement of the center-of-light shift of MACHO microlensing events, which will allow for a model-independent determinations of lens masses.

Keywords: astrometry, interferometry, Keck, extrasolar planets, MACHOs

1. ASTROMETRIC PLANET SEARCHES

1.1 Description of the Instrument & Capabilities

Astrometric detection and characterization of extrasolar planets is an important goal for NASA, and a primary goal of the Keck Interferometer project. The confirmed detection of planets outside our own solar system by radial velocity techniques by Mayor & Queloz[1] and Marcy & Butler[2] has sharply shifted perspectives on searches for such bodies, giving the field a considerable dose of credibility and creating strong impetus to forge ahead with larger, more sensitive planet search programs.

The Keck Interferometer project, in addition to linking the existing twin 10m apertures on an 85m baseline, will add four 1.8m "outrigger" telescopes about the site. These four telescopes will be arranged such that two orthogonal > 100m baselines will be possible simultaneously with pairs of outriggers. The individual outriggers themselves will be highly optimized for astrometric observations, specifically noting: 1) each telescope will have its pivot point known to 35 microns, and 2) each telescope will have a 'dual star module' attached, which will allow for simultaneous interferometric observations of two nearby ($\Delta\theta < 30''$) stars. The first point will allow observational definition of an outrigger-outrigger baseline to better than 4 nm for small areas on the sky (~ 20º), which, in conjunction with the second point, will allow for measurement of relative fringe positions between bright ($m_K < 12.0$) foreground target stars and dim ($m_K < 17.3$) background astrometric references. The accuracy of the differential position will be augmented by end-to-end laser metrology, which will continuously monitor the path lengths traveled by the starlight from the two objects throughout the arms of the interferometer. This observable can in turn be translated into a relative angular separation on the sky of the two objects, accurate to better than 25 μas/$\sqrt{\text{hr}}$. Astrometric observations by the outrigger telescopes will be conducted independent of Keck 1 and Keck 2, and will account for ~50% of the total available observing time. In addition to searching for planets in a region of phase space that is not readily available to radial velocity searches, the Keck Interferometer have the added advantage of being able to solve completely for the orbit, and hence mass, of the detected objects.

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Research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

The requirements upon the instrument's capability to monitor nearby stars for astrometric signatures have been driven by the desire to answer the following general questions (among many):

1) What is the relative frequency of planetary companions, both in general and as a function of spectral type, or some other single- or multiple-parameter stellar characterization?
2) What is the nature of the planetary formation process and its interaction with stellar evolution?
3) Is our own solar system typical or atypical?

The limitations upon the instrument's capability are defined as follows:

1) Cost, specifically as it relates to aperture size. This in turn sets: a) astrometric throughput, and b) availability of reference objects.
2) Target availability, as well-characterized recently by the Hipparcos satellite[3].
3) Astrometric accuracy, as driven by design and cost limitations.
4) As with all projects, a finite amount of annual observing time.

In §2, statistical motivation for a given astrometric sample size will be given, along with characterization of the existing source sample; in §3 astrometric observing time, error budgets and reference sources will be characterized; in §4, representative annual astrometric observations will be tallied; in §5, astrometric performance will be characterized through some simple modeling; and in §6, some other applications of the Keck Interferometer's astrometric capability will be discussed.

2. PLANET SEARCH SOURCE SELECTION

2.1 Statistical Significance Requirements

Detection of a few planets or even a single planet about another star is clearly quite an achievement. Going one step further and being able to make general statements about specific categories of stars and the planetary systems they are apt to possess is an even more challenging task. Selection of an adequately sized sample for an astrometric planetary search is bounded below by the desire to accomplish exactly that task; the sample size is bounded above by the limited about of observing time available annually.

Given a discrete sample of stars of surveyed for planets, binomial statistics were utilized to ascertain the resultant uncertainty associated with detections – specifically, not only is it necessary to measure the relative frequency of planetary companions, but it is also necessary to establish the statistical errors associated with measures of that frequency. Essentially, what is desired are the statistics of the inferences of that can be drawn from the astrometric observing program's finite sample size. The sample size, n, with number of positive detections X, is driven by a desire to minimize the uncertainty σ_X in X, given by:
$\sigma_X = \sqrt{np(1-p)}$, where $p = X/n$.
As evidenced in the equation above, maximum uncertainty in the frequency of planetary systems, σ_p, occurs for p=0.50.

Maximum Uncertainty σ_p	**Sample Size *n***
0.25	4
0.20	6
0.15	12
0.10	24
0.05	96

Also of interest is the likelihood of detecting even a single planetary system with the interferometer. If we pessimistically assume an actual frequency of planetary systems of 10%, we can calculate the probability of detecting one or more systems based upon the sample size:

Sample Size *n*	Single Detection Probability (if *p*=10%)
1	0.10
7	0.52
13	0.75
22	0.90
28	0.95
44	0.990
62	0.999

As such, we need a sample of n=7 at a minimum for the more time-intensive spectral classes (A, F) for at least a 50% chance of planetary detection in each subsample, and n>28 or 44 for 95% and 99% confidence of detection, respectively, in the less time-intensive spectral classes.

2.2 Number of Sources

Using the Hipparcos catalog[3] (rather than the Gliese & Jahreiss's 1991 catalog[5]), and limiting the sources to the sky reasonably accessible from the Mauna Kea site (δ=-41° to 69°, zenith distance z=0 to 60°), the number of sources are as follows:

Distance (pc)	Number of Sources by Spectral Type					Total
	A	F	G	K	M	
0 - 5	1	1	2	6	17	31
5 - 10	4	3	12	31	62	120
10 - 15	10	19	27	63	108	252
15 - 20	5	42	60	135	104	371
20 - 25	13	54	95	183	114	504
25 - 30	27	96	160	233	79	668

Note that the M spectral class counts are declining at 30pc and as such are clearly incomplete at this distance.
Minimum distance for 12, 25, 100 and 250 stars, per spectral type, assuming 35% sky coverage (see §3.5):

Number of Stars	Distance by Spectral Type (pc)				
	A	F	G	K	M
12	15	13	10	6	5
25	23	16	13	9	6
100	> 32	24	20	15	12
250	> 32	32	27	21	18

2.3 Astrometric Signal

From simple geometry and standard Keplerian considerations, the astrometric signal is given by:

$$\alpha_{\mathrm{STAR}} = M_{\mathrm{PLANET}} M_{\mathrm{STAR}}^{-2/3} P^{2/3} \pi = M_{\mathrm{PLANET}} M_{\mathrm{STAR}}^{-2/3} P^{2/3} d^{-1}$$

where α is the astrometric reflex motion on the sky (μas), M's are masses (both in M_{SUN}), P is the period of the orbit (yr), π is the parallax of the system (μas), and d is the distance of the system (pc). Note that Uranus, being the smallest of the giant planets, is utilized as the 'standard mass' in this paper, noting the following relationship:

1 Uranus mass = 14 Earth masses = 1/23 of a Jupiter mass = 1/23,800 of a Solar mass

Orbit assumed is of radius r = 5 AU (roughly a Sun-Jupiter distance). A larger orbit will result in a larger astrometric signature, but also a longer period – and hence, longer period of observations until a detection is made – also results. Given the effect of stellar mass upon astrometric signal, the values have been broken down into two categories: 1 solar mass, roughly typical of F and G class stars, and 0.5 solar mass stars, typical of K and M class stars (see §2.5).

Distance (pc)	Uranus Mass Reflex Motion (μas)	5x Uranus Mass Reflex Motion (μas)	Spectral Types
5	44	221	F, G
10	22	110	
20	11	55	
30	7	37	
5	85	424	K, M
10	43	212	
20	21	106	
30	14	71	

2.4 Relative Observing Time

From the expected astrometric signals listed above (§2.3), the relative amount of on-sky observing time necessary per object can be scaled relative to an expected throughput of 25 μas/√hr:

Distance (pc)	Uranus Mass Reflex Motion (hr)	5x Uranus Mass Reflex Motion (hr)	Spectral Types
5	0.319	0.013	F, G
10	1.276	0.051	
20	5.095	0.204	
30	11.455	0.460	
5	0.086	0.003	K, M
10	0.345	0.014	
20	1.380	0.055	
30	3.102	0.124	

2.5 Stellar Masses

Referencing Allen[6], the expected masses for the stars are as follows:

Mass by Spectral Type (M/M_{SUN})				
A	F	G	K	M
2.09	1.29	0.93	0.69	0.21

2.6 Source Sample

From the above considerations (§2.1-§2.5), the following representative source list has been selected:

Sample	Subsample Size by Spectral Type					
	A	F	G	K	M	Total
Primary	3	13	28	28	44	117
Secondary	13	28	62	62	62	227

In order to maximize the return from the instrument in terms of both quantity and quality, two classes of samples have been defined:

- The **primary** sample is for detection of planets down to Uranus mass at an accuracy of 25 μas; and
- the **secondary** sample is to search a larger number of stars at a lower accuracy of 125 μas.

The small number of stars included in the A class primary search are due to unrealistically long observing times (>8^h for all apertures for 7 or more sources); this is due to sparse distribution of these sources (and hence large distances), and their large masses, both of which contribute to a reduced astrometric signal. As required (§2.1), however, there are n>7 for the spectral class between primary and secondary samples. The maximum and mean target distances resulting from the subsample sizes are listed below (§4.1).

2.7 Statistics of Source Sample

From the source sample we can derive the following statistics (cf. §2.1, §2.6):

Statistic	Sample	Spectral Type A	F	G	K	M
Maximum uncertainty in measured likelihood of planetary companions	Primary	0.41	0.15	0.09	0.09	0.08
	Secondary	0.15	0.09	0.06	0.06	0.06
Probability of 1 or more planet detections, given a 10% likelihood of planetary companions	Primary	0.27	0.75	0.950	0.950	0.990
	Secondary	0.75	0.95	0.999	0.999	0.999

Hence, even within the context of a conservative estimate of 10% of the stars observed having detectable planets, there is ample evidence for confidence of planetary detections for all spectral classes, and down to Uranus mass for all classes but A. These numbers rise accordingly with respect to the degree which 10% underestimates the frequency of planetary systems.

3. PLANET SEARCH OBSERVING PARAMETERS

3.1 Annual Observing Time

The estimation of this value is derived assuming that 50% of the outrigger time will be devoted to the astrometric planetary search. Down time due to weather, calibration, and instrumentation are based upon experience from observing at Mauna Kea, and with PTI.

Annual nights:	365	nights/year
Astrometry portion of outrigger time:	50%	
Hours/night:	10	hours
Losses due to weather:	67%	
Losses due to calibration:	80%	
Losses due to instrumentation:	80%	
Available time:	779	hours/year

3.2 Astrometry Error Budget

As derived for the Keck Interferometer preliminary design review, the following error budget specifically enumerates the expected contributions to the astrometric error.

Error Term	**Size**	
Atmosphere	4.85	nm
Photon noise	9.10	nm
Baseline noise	3.70	nm
Baseline solution	1.90	nm
DCR	2.50	nm
Starlight/metrology	2.00	nm
CT alignment	2.10	nm
CT laser stability	0.60	nm
CT thermal	2.50	nm
BC measurement error	3.50	nm
Total noise	12.12	nm = 25.0 μas/√hr

Specific explanations of the terms are as follows:
Atmosphere – Based upon measured Mauna Kea turbulence profiles and an integration time of one hour[7].

Photon Noise – Based upon observing a dim astrometric reference star for one hour (see §3.3 below).
Baseline Noise – Non-modelable motion of the effective baseline.
Baseline Solution – Errors in solution for baseline from wide-angle astrometry.
DCR – The effect of differential chromatic refraction of the starlight as it passes through the atmosphere, across the K band.
Starlight/metrology – Residual errors due to differential sampling by starlight and metrology beams.
CT Alignment – Running throughout the beam path from telescope to beam combiner to telescope is a laser metrology system referred to as the continuous term (CT) metrology; one CT path exists for each of the two starlight paths, allowing for continuous monitoring of differential beam path lengths between the two stars. Misalignment of the optic axis of the CT system relative to the starlight optic axes constitutes to this error term.
CT Laser Stability – Attributable to frequency drifts of the CT source laser.
CT Thermal – Due to non-common path optics between starlight and metrology beams.
BC Measurement Error – Nonlinearities in measuring the starlight phase.
Total Noise – Added in quadrature. A 12.1 nm of error on a 100 m baseline corresponds to a 25 μas angular error.

3.3 Astrometric Limit (Throughput) Of Aperture Size

Photon noise for the astrometric source can be written as[7]:

$$\sigma_{\mathrm{PN}} = \frac{\lambda}{2\pi B \times \mathrm{SNR}} = \frac{722\mu\mathrm{as}}{\mathrm{SNR}}$$

where the latter values are derived using $\lambda = 2.2\mu$m and B = 100m. Hence, a reasonable expectation for an astrometric source is SNR=25-125 in one hour. Estimates of the instrument's limiting sensitivity were developed for the Keck Interferometer preliminary design review and can be used to determine limiting magnitude in one hour of integration time:

SNR	Aperture diameter (m)		
	1.5	1.8	2.0
25	17.8	18.2	18.4
50	17.0	17.4	17.6
75	16.6	16.9	17.2
100	16.2	16.6	16.8
125	16.0	16.4	16.6

Note that different Strehls for the variously sized apertures are accounted for in this calculation. For a photon noise of 9.10nm = 18.77 μas (as listed in the error budget in §3.2), SNR = 38.5. This corresponds to m_K = 17.3, 17.7, and 17.9 for 1.5, 1.8 and 2.0m apertures, respectively. Alternatively, for a 1.5m aperture operating at a SNR = 38.5 with a m_K = 17.3 star, 1.8m and 2.0m apertures will be operating at SNR = 54.9 and 67.2, respectively, for a photon noise of 13.2 nm and 10.7 nm, respectively. For these apertures, the total astrometric error rate will be 21.1 μas/√hr and 19.7 μas/√hr (as compared to the 25.0 μas/√hr rate for a 1.5m aperture.) For a comparable 25.0 μas/√hr astrometric error, the 1.8m and 2.0m apertures operate at 1.40x and 1.61x the throughput of the 1.5m aperture.

3.4 Sky Availability Of Foreground References

Given that the expected fringe-tracking ("cophasing") limit of even the 1.5 m aperture is m_K = 10.4, we expect virtually all of the foreground astrometric targets within 30 pc to be utilizable as cophasing sources.

3.5 Sky Availability Of Astrometric References

Using V band sky counts from Allen[6] (assuming a mean galactic latitude of l = 30°) and assuming a V-K color of 3 (assumes a mean spectral type of K5V)[8], we can estimate the probability of two or more sources within an isoplanatic patch, which is conservatively assumed to be 20" at 2.2 μm for Mauna Kea.

Limiting m_K	Number of sources expected in a 20" radius	Probability of two or more sources
16.0	0.770	0.181
16.4	0.926	0.237
16.8	1.113	0.306
17.2	1.338	0.387
17.6	1.609	0.478
18.0	1.935	0.576

Two, rather than one, astrometric references will be required to confidently isolate astrometric perturbations to the bright foreground star of interest. A K5V star will be 0.7 solar masses; such a star at 2 kpc with a 0.02 solar mass brown dwarf companion would be a bright potential astrometric reference candidate at $m_K = 16.0$, while exhibiting a 65 μas astrometric signal of its own. A 0.08 solar mass companion (roughly the low end of the stellar sequence) to that reference would exhibit an even larger 270 μas signal. Alternate avenues, such as radial velocity characterization of the background astrometric references, are being explored to reduce the required number from two to one, and reap the corresponding windfall in both additional observing time and sky coverage, noting that current radial velocity techniques would not be sufficient to detect either example given above. Hence, for the purposes of this paper, we will conservatively continue with the expectation that two astrometric references are required. Hence, for $m_K = 17.3$ (§3.3), $P(x > 1) = 0.409$.

4. ANNUAL PLANET SEARCH OBSERVATIONS

4.1 Sample Distance

Given a 40.9% probability of two or more astrometric references (§3.5), the distance of the primary and secondary samples are as follows, given the necessary sample size (§2.6):

Parameter	Sample	Spectral Type				
		A	F	G	K	M
Maximum Distance	Primary	11	17	17	13	11
	Secondary	25	23	25	19	18
Mean Distance	Primary	8.7	13.5	13.5	10.3	8.7
	Secondary	19.8	18.3	19.8	15.1	14.3

The geometric average (the mean with respect to the volume indicated by the maximum distance, $= (d_{MAX}^3 / 2)^{1/3}$), rather than the maximum, was utilized in determination of the astrometric parameters. Note that the distance of the secondary sample is 'pushed out' by the use of the closest stars of a given spectral class for the primary sample; e.g., the nearest 62 G-class stars are within 22pc, not 25pc, but 28 of those 62 are already being observed in the primary sample.

4.2 Observing Time by Spectral Type

Scaled relative to 25 μas/√hr, the relative necessary observing time is as follows, based upon sample distance (§4.1), a 1.5 m outrigger aperture size, and target mass (§2.5):

Sample	Spectral Type				
	A	F	G	K	M
Primary	4.66	4.23	2.22	0.71	0.05
Secondary	0.96	0.31	0.19	0.06	0.01

Astrometric signature is based upon orbit assumed for the target of radius $r = 5$ AU. Also, as noted in §3.3, the 1.8m and 2.0m apertures have a 1.40x and 1.61x advantage in throughput, respectively, over the 1.5m aperture.

4.3 Expected Observing Time Required

The representative observing program (§2.6) and a 1.8 m outrigger aperture size were utilized in estimating the amount of observing time needed annually for the astrometric program. 'Total time by type and target' is calculated by multiplying the 'number of stars' by both the 'observing time per star per reference' and a factor of two, representing two astrometric reference stars per target (as discussed in §3.5).

Detection Limit	Parameter	Spectral type					Total Time (hr)
		A	F	G	K	M	
Primary Targets: 1 Uranus Mass	Number of stars	3	13	28	28	44	
	Source distance (maximum)	11	17	17	13	11	
	Observing time per star per reference	3.33	3.02	1.59	0.51	0.03	
	Total time by type & target	20.0	78.6	88.9	28.6	3.1	219
Secondary Targets: 5 Uranus Masses	Number of stars	13	28	62	62	62	
	Source distance (maximum)	25	23	25	19	18	
	Observing time per star per reference	0.69	0.22	0.14	0.04	0.00	
	Total time by type & target	17.9	12.4	17.1	5.4	0.5	53
	Slew time	343	stars, 2 x 3minutes each			0.100	34
	Subtotal						307
	Times/year						2.5
	Total						767

Comparing the final value to the amount of expected annual astrometric observing time (§3.1), it may be seen that we are within the anticipated value of ~780 hours.

5. PLANET DETECTION SIMULATIONS

Likelihood of detection of planetary systems by means of observed astrometric signatures is a well-analyzed problem[9], with equally well-developed estimators for false positive detections[10]. As a verification of the ability of the Keck Interferometer to detect objects at the limit, two simulations were run to test that hypothesis: (1) a single Uranus-mass object in a 5 AU (Jupiter-like) orbit about a solar analog at a distance of 20 pc, and (2) a sentimental favorite, our own solar system at a distance of 20 pc. For the first case, data points were assumed to be taken every 150 days (roughly 2½ times a year) for 10 years, and at an accuracy of 25 µas. The second case is as the first, but over 15 years, and with 125 µas accuracy. Regular spacing of the data points in time was assumed for simplicity but by no means is an actual constraint on actual observations.

Using heliocentric planetary coordinates available from NSSDC[11], time-dependent astrometric displacements in two coordinates were calculated based upon expected mass and distance of object(s) from the primary. The projection geometry was assumed to be face-on at the 20 pc distance for the sake of simplicity. Added to those values were the prescribed random noise values; the resultant data samples were used as input into a periodogram analysis as defined by Scargle[12]. In both of the test cases, the largest mass planet was detectable with a false alarm probability of less than 0.1%.

The distinction between *detection* versus *characterization* is an important one; specifically, the number of data points required to detect the largest planet in a system is far less than the number required to fully characterize the orbits of all the objects in a multiple component system. This is true even if the astrometric signature of each planet is substantially above the detection threshold for the interferometer. To compensate for the necessity for additional data to characterize detected planetary system, the expectation is that positive planetary detections for given stars will result in their reassignment to a higher priority queue for observations. It should be noted that data that spans less than a planetary orbital period can be utilized in detecting a planet, depending upon signal-to-noise; however, orbital characterizations will be subject to serious biases that persist even after two full orbits have been observed[9]. However, these subtle issues involved in fully modeling and analyzing system characterization are beyond the scope of this paper and will receive a proper treatment in an upcoming publication.

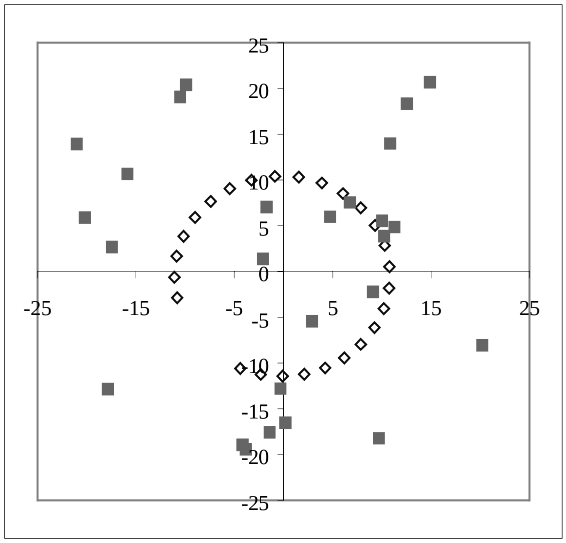

Figure 1. Astrometric signal of a 1 Uranus mass object in a 5 AU orbit about a 1 solar mass star at a distance of 20 pc. Diamonds represent the true values, while squares are 10 years' worth of measurements at 150 day intervals, with 25 μas errors; both axes are in μas. Simple Monte Carlo modelling indicates such an object is easily detectable from the data.

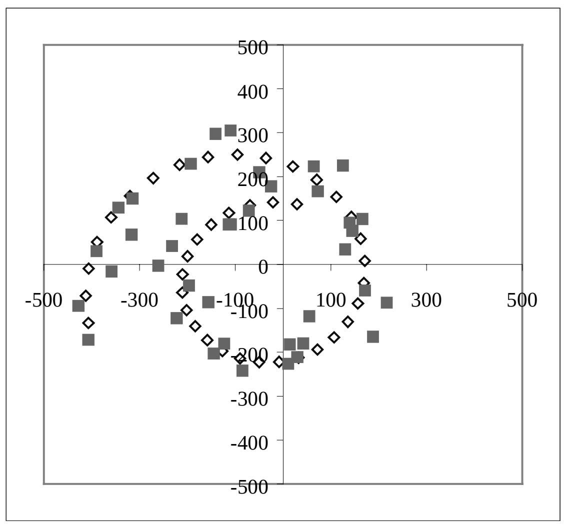

Figure 2. Astrometric signal of our own solar system at a distance of 20 pc. Diamonds represent the true values, while squares are 15 years' worth of measurements at 150 day intervals, with 125 μas errors; both axes are in μas. Simple Monte Carlo modelling indicates that Jupiter is easily detectable from the data. Detection of Saturn, Uranus and Neptune will depend upon length of the astrometric program, annual frequency of observations, and signal-to-noise ratio.

6. OTHER ASTROMETRIC ASTROPHYSICS

The astrometric ability of the Keck Interferometer will also be utilized to provide unique results in areas other than the search for extrasolar planets. Most obviously, there will be a considerable body of 'collateral' science that will fall out of the planet search itself – specifically, a sizeable number of binary stars will be detected in both the foreground and background stars. While discussed in §3.5 (with respect to the background stars) as undesirable noise in the planet search program, these objects represent valuable targets in their own right, albeit non-planetary ones. The option to spend a small amount of additional observing time to have their orbits characterized will exist. Accurate mass measurements still only exist for a small sample of stars, primarily specific binary star systems[13]; orbital characterization of a properly selected sample of detected binaries would provide new measurements for stellar mass, in addition to distances and luminosities.

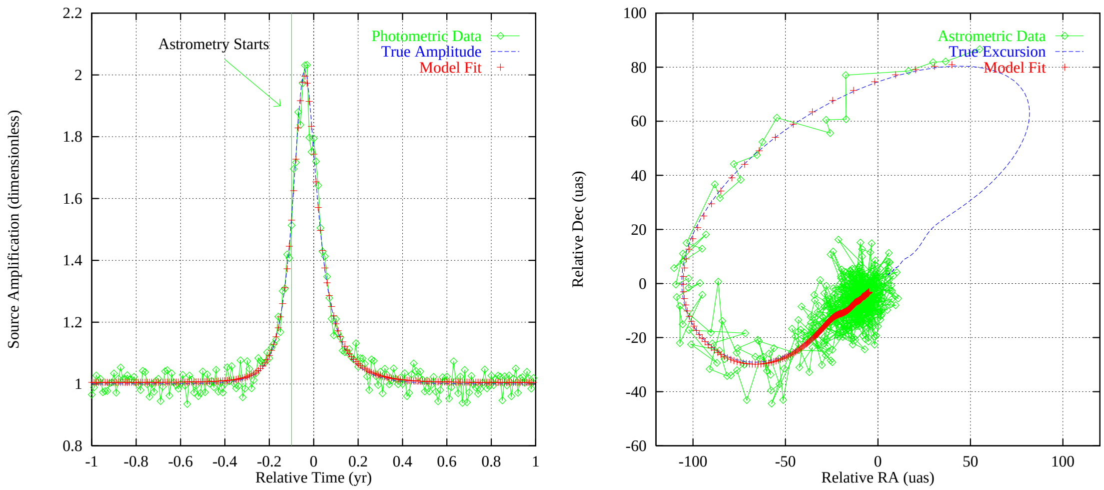

Figure 3. Sample Microlensing Model Fitting. Here we show an example instance of fitting a microlensing model to synthetic terrestrial photometry and astrometry datasets for a microlensing encounter. The critical parameters for the event are a lens motion position angle of 30°, p=0.4, r_E=300 μas, and Π=100 μas (m=0.1 M_{SUN}). We assume the event is identified photometrically, and the differential astrometric measurements commence after that detection. The microlensing model was simultaneously fit to both photometric and astrometric data. Shown in each are the simulated data, true values, and the model fit. Left: the photometric lightcurve results. Right: the corresponding depiction for the astrometry sequence relative to the nominal source position.

Also, as outlined in detail in Boden *et al.*[14], the interferometer will be able to astrometrically observe center-of-light shifts in MACHO events, allowing for model-independent solutions for the lens mass. Ten years ago Paczynski[15] suggested that photometric observations of gravitational microlensing might be used to indirectly study the population of massive compact objects in the galaxy, and in particular Massive Compact Halo Objects (MACHOs) that might be a significant component of the dark matter thought to exist in the galaxy by dynamical considerations. Over the past several years, Paczynski's suggestion has been confirmed, and currently there are no less than four groups that have reported significant numbers of candidate gravitational microlensing events from photometric observations of the LMC, SMC, and galactic bulge sources. The MACHO collaboration estimates that roughly half of the expected dark matter in the galactic halo is in the form of dark stellar mass objects such as white dwarfs[16]. The difficulty in interpreting the MACHO collaboration events is that they are observed photometrically, which does not uniquely determine the mass of the lens - instead, the MACHO collaboration bases their conclusions on interpreting their event sample observables (amplification, duration) in the context of a halo model[16].

Clearly it is desirable to measure MACHO physical properties in a model-free context. This objective has led a number of authors to propose the astrometric observation of MACHO gravitation microlensing events[17,18], a specialized application of an earlier suggestion by Hosokawa *et al.* [19]. High-precision astrometric observation of the lensed center-of-light allows the estimation of the lens parameters (mass, distance, proper motion) appealing only to the properties of lensing. The lens mass can be directly measured independent of additional assumptions, and the lens distance and transverse velocity can be estimated by appealing to an independent model of source distance and proper motion.

The problem of determining this subset of the lens parameters, in particular the lens mass, is particularly amenable to the narrow-angle differential astrometric capabilities of the Keck Interferometer, as discussed in Boden *et al.* [14]. A program to probe microlensing events photometrically detected in the galactic bulge is planned for the interferometer. As currently reported by the MACHO Project[20], there have been 49 bulge microlensing events detected in this year alone, with an average (nonlensed) V magnitude of 19.2. Assuming a V-K color of 2.9 (consistent with an average spectral type of K5, as indicated by the given average V-R color of 0.9), the average K magnitude is 16.3, which is brighter than the limiting astrometric magnitude of 17.3. The MACHO targets represent the dim background astrometric object, and as such need a chance bright foreground star for cophasing the interferometer; since these are bulge events, they should have a significantly higher probability of a bright foreground reference than the all-sky 5% average probability. Assuming 25% sky coverage for the bulge events, roughly 10 events a year could be examined by the Keck Interferometer. The expected 25 μas astrometric performance of the interferometer yields microlensing parameter estimates sufficient to constrain lens parameters for individual events, which will give profound insight into the nature of these objects.

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