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The CHARA Array as an ASEPS Resource

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1. INTRODUCTION

The Center for High Angular Resolution Astronomy (CHARA) of Georgia State University will build a facility for optical/infrared multi-telescope interferometry, called the CHARA Array. This array will consist of initially five (with a goal of seven) telescopes distributed over an area approximately 350 m across. The light beams from the individual telescopes will be transported through evacuated pipes to a central laboratory, which will contain optical delay lines, beam combination optics, and detection systems. The facility will consist of these components plus the associated buildings and support equipment, and will be located at the Mount Wilson Observatory in southern California. The CHARA Array is funded by Georgia State University and the National Science Foundation.

The CHARA Array will have a unique capability — the resolution will greatly exceed either the proposed Keck interferometer or the VLTI. The collecting aperture exceeds any currently funded project. Two spectral operating regimes are planned, a visible window at 0.5 to 1.0 μm and an infrared window across 1.0 to 2.5 μm. The limiting resolutions, accuracies, and magnitudes are: 200 μas, ± 20 μas, and +11 mag at V and 1,000 μas, ± 35 μas, and +15 at K. In this Technical Report, we discuss potential contributions the Array can make to the detection of extra-solar Jupiter mass planets. It will be shown that the facility can contribute significantly to NASA's "Astronomical Studies of Extra-Solar Planetary Systems" (ASEPS) program as early as 1999 when the initial telescopes are installed and operational.

Four areas of relevance to ASEPS are envisioned for the Array:

1. Astrometry of visual binaries — This approach relies upon the high degree of accuracy with which the Array can measure the relative positions of the components of visual binaries, an area in which CHARA has very extensive expertise. Jupiter-mass planets would reveal themselves as submotions in residuals to orbit solutions with high signal to noise ratios. We show here that the Array will perform astrometry with an accuracy of ± 20 μas for a conservatively defined candidate sample of 466 binary systems. Uranus-mass planets could be detected in the nearest and lowest mass binaries.

2. Structure within protostellar disks — Imaging at K-band provides the potential for

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detecting structures within disks surrounding YSO's that may reveal the initial stages of planetary accretion. Such structures include gaps and rings which would be well resolved at the distance of the Taurus and Ophiuchus star forming regions for which the CHARA Array would possess a limiting spatial resolution of 0.15 AU. To optimize this capability, additional telescopes are desirable to enhance (u, v)-plane coverage, and we describe two potential ways in which this enhancement can be obtained. We note that the imaging of YSO's is one of our original primary scientific justifications.

3. Imaging of microlensing events — The limiting resolution of the Array would permit the measurement of the Einstein ring geometry produced when a galactic disk lensing star passes in front of a K giant star in the galactic bulge. This "Macho" approach is emerging as a powerful means for detecting even Earth-mass planets in very distant systems. Measurements of the event geometry combined with satellite observations from which the parallax of the lensing star is measured allows the determination of the mass of a planet discovered through such an event.

4. "Narrow angle" Interferometry of nearby stars — The method first proposed by Shao & Colavita (1992) for very high precision differential astrometry at K-band can potentially be applied at the CHARA Array following extensive modifications of the optical configuration of the instrument to enable simultaneous two-beam interferometry. If such modifications are feasible, the Array would have a capability intermediate between the Palomar Testbed Interferometer (PTI) and the proposed Keck interferometric array including the planned 2 m aperture outrigger telescopes on Mauna Kea. With the limited aperture of the CHARA telescopes, the potential observing program would be significantly restricted compared with the Keck interferometer.

2. INTERFEROMETRIC ASTROMETRY OF BINARY STARS

Binaries are often overlooked in surveys for extra-solar planets due to difficulties they impose on various observational techniques through image overlap, spectral line blends, etc. Because the majority of stars are found within binary and multiple stars, the exclusion of such systems from surveys for other planets very significantly diminishes the search space and biases the results. There are presently no compelling theoretical reasons opposing the existence of planets within binary stars other than the condition of hierarchical orbits for long-term stability (Harrington 1977, Black 1982, Donnison & Kikulskis 1992). That condition requires that the ratio of orbital semimajor axes between the stellar system and a star-planet system be no smaller than 5.0 to 5.5.

Interferometric methods provide an ideal means for searching for astrometric submotions in binaries resulting from the orbital motion of a planet around one component of the stellar system. This approach was first suggested by McAlister (1977) who proposed the use of speckle interferometry as a means for discovering Jupiter mass planets in nearby binaries. While speckle methods have not yet yielded any planets, the submotions of unseen stellar mass companions have been found in the case of ADS 784 (Cole et al. 1992) and ξ Ursa Majoris (Mason et al. 1995). These detections, the first by means of any interferometric technique, resulted from speckle observations with measurement accuracies of approximately $\pm$2–3 mas.

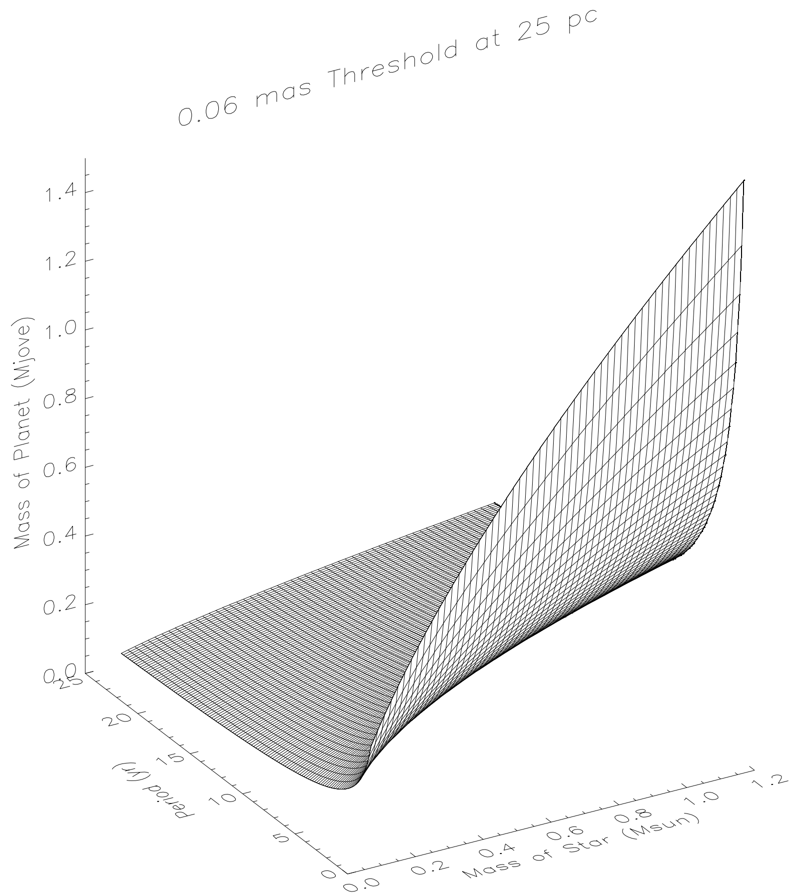

FIGURE 1. The planetary detection threshold from equation (1) is shown for a 60 μas stellar submotion at a distance of 25 pc. The volume above the threshold sheet represents planetary masses detectable as a function of parent stellar mass and planetary orbital period. In the extreme case, a Uranus-mass planet in a 25-year orbit about an M dwarf star would be discoverable.

2.1. Defining the survey sample

As will be shown in Section 2.2.2, the limiting binary star accuracy in a single measurement anticipated for the CHARA Array is $\pm 20\,\mu$as, a gain of 100 over speckle interferometry. This limiting accuracy is conservatively derived from assuming centroiding to 0.05 pixels. An equally conservative estimate for the detection threshold is obtained by requiring that the planetary induced submotion be three times the accuracy of a single measurement, although a single planet would produce a strictly periodic variation that would be detectable over time even if the amplitude were smaller than $\pm 20\,\mu$as.

It can be shown that the reflex motion (in arcsec) of a star orbited by a planet is:

$$\alpha_\star = M_p M_\star^{-2/3} P_p^{2/3} d^{-1} \qquad (1)$$

where the mass of the planet M_p and the mass of the star $M_\star$ are in solar masses, the planetary orbital period P is in years, and the distance d is in pc. Figure 1 indicates the lower limit of detectable planetary masses assuming a detection threshold of 60 μas at a distance of 25 pc. At that distance, a planet as small as 0.04 Jupiters (i.e. somewhat less than the mass of Uranus) orbiting around an M dwarf star with a period of 25 years would be detected.

We specifically consider a target detection regime defined by: a Jupiter-mass planet in the range of 3 to 10 AU from a one solar-mass primary star in a two solar mass binary; a detection threshold of 60 μas; fulfillment of a hierarchical condition with a ratio of stellar to planetary semimajor axes of six; and, a maximum angular separation of the binary limited by the Array's vignetting limited field-of-view of 1.3 arcsec. Under these criteria, the above relation leads to a maximum distance beyond which a planetary perturbation would not be detectable of:

$$d_{max} = 16.7 M_{\star}^{-2/3} P_p^{2/3} = 16.7 M_{\star}^{-2/3} a_p \tag{2}$$

where a_p is the planetary orbital semimajor axis. The sensitivity to mass of the parent star implies that d_{max} increases with decreasing distance to the extent, for example, that a Jupiter around a K5V parent star would be detectable out to a distance 28% greater than in the case of a G2V star.

A minimum distance is encountered for a given system due to the limited field-of-view such that binaries closer than d_{min} would have angular separations exceeding 1.3 arcsec. In the case of an appropriately hierarchical orbit of zero inclination, this minimum distance is given by:

$$d_{min} = 4.6 P_p^{2/3} = 4.6 a_p. \tag{3}$$

The following table presents a summary of distance regimes over which particular planetary orbit semimajor axes are detectable in a binary system comprised of two solar type stars with a Jupiter in orbit about one of them. The final column gives the apparent V magnitude of a G2V star at the minimum and maximum distances. The minimum and maximum distances range from $4.6\times a_p$ to $8.3\times a_p$.

a_p (AU)	P_p (yr)	$a_\star$ (AU)	$P_\star$ (yr)	d_{min} (pc)	d_{max} (pc)	V_{min}	V_{max}
3.0	5.2	18.0	54.0	13.8	50.1	5.5	8.3
5.0	11.2	30.0	116.2	23.0	83.5	6.6	9.4
7.5	20.5	45.0	213.5	34.5	125.3	7.2	10.3
10.0	31.6	60.0	328.6	46.0	167.0	8.1	10.9

The constraints discussed in this section thus define a rather peculiar volume of space over which a planet search in binaries can be conducted. Nevertheless, the search regime is significantly larger than that occupied by the Gliese stars. A search of the Washington Double Star Catalog (maintained by C. Worley at the U.S. Naval Observatory) for systems within 45° of the zenith of Mt. Wilson in the angular separation regime 0.8 to 1.3 arcsec and having primary and secondary limiting magnitudes brighter than $V = +11$ and $+13$ respectively reveals 466 candidate objects with primary stars of spectral type F to G5 for an interferometric survey of planets with binaries. The limiting magnitude of the sample primary stars coincides with the anticipated limiting V magnitude of the Array. Fringe tracking will be done using the primary star, and so the secondary star of the binary can be significantly fainter. We thus have a substantial list of objects constituting a major potential contribution to the ASEPS effort.

2.2. Dual Envelope Tracking

The field of view of the CHARA Array in the 'normal' observing mode is ultimately limited by the size of the Airy disks produced by the optical input channels. For the full apertures this is of the order of 0.1 arcsec. To do astrometry on binary systems with the larger separations encountered in our list of candidate stars requires a different technique described here as "dual envelope tracking." This method is essentially that of Dyck et al. (1995).

Each star in a binary system will produce a fringe packet, and the difference in group delay of the two fringe envelopes is a measurement of the angular separation. It would not be necessary to actually measure the fringe magnitudes, only the position of the fringe envelopes. Both fringe packets will be formed from images in the same isoplanatic patch of the sky and in the case of a chopped system within the same coherence time. Thus, atmospheric effects will be no worse than they are in a more standard measurement mode. There are a number of ways in which this measurement could be performed with the CHARA Array. For example,

- For the brighter objects no hardware changes need to be made; the optical path length equalizers (OPLEs) are capable of chopping between two delay lengths. The fringe tracking system could then be used to measure the positions of the two fringe envelopes. The chopping would need to be performed in times less than the coherence time of the atmosphere, but this capability is already a part of the proposed OPLE system.
- We could add a fiber stretching facility to the design of the imaging system (cf. Shaklan 1990, Peiqian et al. 1995). In this way it would be possible to chop between the two stars and achieve similar results. The magnitude limit would probably be improved over the method outlined above as the fringe tracking system would remain independent of the measurement.
- If the location reserved for the imaging system were used instead for a second fringe tracking system, as is planned for the Array, along with small optical delay lines it would be possible to use the channeled spectra to measure the location of the two fringe packets.

2.2.1. Range for Delay lines/Fiber Stretchers

The separation of the two fringe envelopes x depends on the projected baseline B and the angular separation of the stars θ via

$$x = B\theta. \tag{4}$$

For the maximum baseline of 354 m and a separation of 1 arcsec this results in a differential delay of approximately 2 mm. Clearly, it will not be necessary to have large secondary delay lines, nor does the temporal bandwidth need to be as large as the main OPLE system. Since the two fringe packets will essentially undergo the same path length variations due to the atmosphere, only the main OPLEs need be used to track both sets of fringes. A small cat's eye or fiber stretching system will be adequate.

2.2.2. Measurement precision

The precision of the channeled spectrum in measuring the group delay of a fringe packet depends primarily on the bandwidth of the spectrometer being used. The group delay of the fringe packet is given by

$$x = \frac{P}{\Delta\kappa} \tag{5}$$

where P is the number of channel fringes across the spectrum and $\Delta\kappa$ is the bandwidth in wavenumber:

$$\Delta\kappa = \frac{1}{\lambda_{\rm min}} - \frac{1}{\lambda_{\rm max}}. \tag{6}$$

The precision of the measurement, when simply looking for a peak in the Fourier transform of the spectrum is $1/\Delta\kappa$. If the spectra are logged, it should be possible to perform post-processing and conservatively estimate the position of the peak using a least squares fit to one twentieth of this pixel size (i.e. $\Delta x \approx 0.05/\Delta\kappa$). The angular precision will therefore be

$$\Delta\theta = \frac{\Delta x}{B} = \frac{0.05}{\Delta\kappa\, B}. \tag{7}$$

In the optical band, we could make measurements from 0.4 to 0.9 μm, and therefore we have the following results for a range of baselines:

Baseline (m)	$\Delta\theta$ (μarcsec)
20	350
50	140
100	70
200	35
354	20

In the K-band infrared (2.0 μm - 2.4 μm), using the group delay method would lead to significantly larger errors ($\approx$ 350 μas). In this regime we propose to concentrate on measurement of accurate visibilities, as in our 1994 CHARA proposal to the National Science Foundation. Simulations indicate that the main limitations are the diameters of the stars and the visibility accuracies. For example, for a binary with a separation of 400 mas, star diameters of 1 mas, and visibility measurement accuracies of 0.02, a positional accuracy of $\Delta\theta = 35$ μas is feasible. Thus the K-band measurements have accuracy comparable to that in the visible operating regime.

2.2.3. Range of separations possible

We can use something similar to the Rayleigh criterion to set a minimum separation for the stars. The minimum separation occurs when the first minimum of one fringe packet is at the position of the maximum of the second fringe packet. The size of the fringe envelopes are determined by the optical bandwidth of the individual pixels on the detector. We therefore get

$$\theta_{\rm min} = \frac{N_{\rm pix}}{\Delta\kappa B}. \tag{8}$$

For the currently planned CHARA visible system using 128 pixels this ranges from about 1 arcsec for a 20 m baseline down to 50 mas for the largest baseline of 354 m.

The maximum separation depends on many factors such as the field of view of the telescopes and the length of the optical systems. Ultimately the beams for one of the stellar images will be vignetted by the optical system and fringes will not be produced. If we say that the beam movement can be up to some fraction of the beam diameter Δl we get

$$\theta_{\rm max} = \frac{\Delta l}{8D} \tag{9}$$

where D is the optical path length inside the interferometer and the factor of 8 appears because of the telescopes' beam reduction. If we set the internal path length to approximately 400 m and allow the beams to move up to $\pm 10\%$ of the beam diameter (Δ l = 0.024 m), we get a maximum separation of the order of 1.3 arcsec.

2.2.4. Summary

With a modification of observing technique, a second fringe tracking system, or a fiber stretching facility for the imaging system, it would be possible to perform astrometry on binaries in the range of 0.1 to 1.3 arcsec with a precision up to 20 μas. Stars with a separation less than 0.1 arcsec could be measured using a more standard interferometric technique, although it was shown in the previous section that such systems are not candidates for planetary submotion detection.

3. STRUCTURE IN DISKS SURROUNDING YSO'S

Spectral energy distributions at infrared and mm wavelengths indicate that up to 100% of young stars of mass less than one solar mass have disks. These disks are very likely related to the origin of planetary systems. The evolution within such disks that leads to the formation of planets could produce structures such as inner holes and annular gaps that could be detectable through high resolution imaging. Disks which absorb and then reradiate stellar radiation may have a luminosity of 0.25 to 0.5 that of the stars (Kenyon and Hartmann 1987). Since most of this flux is emitted in the infrared, the disk will dominate the observed IR flux distribution. The cross-over from photospheric to disk emission typically occurs in the range 1.5 to 3 μm, hence the 2.2 μm window is an excellent spectral region for observing the star-disk relationship.

At 0.6 μm, the Array will resolve a K5 star of magnitude K = +7 or brighter (about 20 such young stellar objects exist in the Taurus region), and at 2.2 μm will resolve the region of the disk dominating the 2.2 μm emission. It will be possible to determine, initially, the relative locations of the boundary and disk emission, and eventually to obtain images of these regions. Spatial resolution at several wavelengths will determine size and temperature of emitting regions much more strongly than integrated photometry alone. Images in polarized light will reveal the influence of scattering.

At a distance of 150 pc, corresponding to the distance of the Taurus and Ophiuchus star forming regions, the limiting resolution of the CHARA Array at the K-band of 1 mas corresponds to 0.15 AU. A 100 AU-diameter disk would thus be hundreds of pixels across. Assuming the central source is point like, then such disks have enticing imaging potential. As many of the sources are bright in both visible and IR spectral windows, it will be advantageous to use visible light for wavefront tilt and fringe stabilization, while the infrared detector system integrates on the source fringe pattern. This will make it possible to achieve much higher dynamic range in infrared imaging than would otherwise be possible.

The current design for the Array, incorporating five telescopes, is optimized for uniform (u, v)-plane coverage at the highest limiting resolution. In the application to imaging disks, the disks themselves are greatly overresolved. It would be desirable to significantly increase (u, v) coverage through the addition of two or more telescopes to provide additional moderate baselines in the 10 to 100 m regime. This upgrade of the Array would then permit the optimal imaging capability for this important ASEPS problem.

Additional telescope resources on Mt. Wilson provide intriguing possibilities for increasing (u, v) coverage. The 60-inch and 100-inch telescopes provide additional sampling of the (u, v) plane, with the former telescope situated so as to provide the needed moderate additional baselines when paired with the two 1-m telescopes envisioned for the southern arm of the Array. The feasibility of including these telescopes in the Array, possibly through fiber optic feeds at infrared wavelengths, has yet to be explored.

Another pathway towards (u, v) expansion is the occasional relocation of the telescopes of the Berkeley Infrared Spatial Interferometer (ISI) with whom the CHARA Array will be neighbors. ISI currently consists of two 1.65-m siderostats, with a third being requested from the NSF. Discussions over the desirability and feasibility of locating these instruments for selected experiments within the CHARA Array have been initiated between CHARA and the Berkeley investigators.

4. MICROLENSING EVENTS AS A MEANS OF DETECTING EXTRA-SOLAR PLANETS

There is currently great interest in the detection of "massive compact objects" (Machos) towards the galactic bulge and the Magellanic clouds through microlensing events. The method of detecting planetary mass objects through the circumstances of microlensing events has been described by Gould & Loeb (1992). The chance passage of a galactic disk lensing object at a distance of 2 to 4 kpc in front of a galactic bulge object at a distance of 8 kpc produces an Einstein ring enhancement of the light from the bulge object amounting to an increase in brightness of 1 to 2 magnitudes during the event lasting of the order of 1 to 2 months. Over 50 such events have been detected to date through the so-called MACHO collaboration. A planet surrounding the lensing object participates in this event through the short time enhancement of the light by approximately 1 to 10% for 10 to 50 hours depending upon circumstances of the event and the planetary mass. Planets within 1.5 to 3.0 AU of a 0.3 solar-mass lensing star will contribute to the lensing event with the distance sensitivity scaling as $M_\star^{0.5}$. The program requires the monitoring of very large numbers of stars. In the event of a detection of a planetary enhancement of an event, the CHARA Array would be used to measure the shape and size of the Einstein rings during and after the event.

Equation 2.2 of Gould & Loeb (1992) can be rewritten in familiar terms as

$$\theta = 1.01 \cdot (M D_{\rm ls}/D_{\rm ol})^{0.5} \quad \text{(milliarcsec)} \tag{10}$$

where θ is the radius of the Einstein ring with the distance to the source assumed to be 9 kpc for a galactic bulge object, M is the lensing star mass in solar masses, $\rm D_{ls}$ = distance from lens to source, and $D_{\rm ol}$ = distance from observer to lens. Inspection of this relation and recognizing that

$$D_{\rm ls}/D_{\rm ol} \ \le \ 1.0 \tag{11}$$

for the event circumstances shows that the ability of the CHARA Array to resolve the Einstein rings is enhanced for lensing stars of at least one solar mass located halfway to the source star. In such events, the diameter of the Einstein rings will be approximately twice the resolution limit of the Array. If we assume that the source object is a K0III giant star at a distance of 8 kpc, it will have an apparent V magnitude of +15 (which will be heavily obscured by intervening dust) and a K magnitude of +13. such an object is accessible in the infrared to the Array. The ring will be of comparable or greater total brightness.

By following the progress of the event, structure at the Einstein radius can be followed leading to a determination of the proper motion of the event. When this proper motion is combined with the parallax of the lensing object, which can be ascertained in certain circumstances from ground-based observations or more generally from a spacecraft orbiting the sun at 1 AU, the mass of the lensing object can be determined (Gould 1995). If the lensing event also exhibits a secondary event arising from a planet, then the mass of the planet can be measured. Because the CHARA Array will be able to detect structures at the Einstein radius for certain classes of microlensing events, it can potentially provide complementary information leading to values for the masses of the parent star and its planet(s).

5. "NARROW ANGLE" INTERFEROMETRY

The principles of narrow angle interferometry were first described by Shao & Colavita (1992), who showed that long-baseline interferometers can take advantage of the properties of atmospheric turbulence in the infrared to achieve exceptionally high accuracy in applications of differential astrometry provided a reference star can be found within a few tens of arcseconds from the program star. This condition requires the use of relatively faint reference stars, but luminosity functions show the high probability of finding background K stars within the required angle of a much brighter program star, especially at low galactic latitudes. Shao & Colavita (1992) showed that the technique is especially promising when large aperture interferometers, such as the proposed Keck Interferometer and the European VLT Interferometer, are equipped for this application. In order to test the principles of narrow angle interferometry, a testbed facility is currently being constructed on Mt. Palomar (the PTI) by the Jet Propulsion Laboratory. This facility is described by Colavita et al. (1994) and is expected to be operational in the fall of 1995. It is considered to be a stepping stone towards a major undertaking at the Keck telescopes for interferometric detection of extrasolar planets, a facility that would become the ground-based flagship of ASEPS-1.

Shao & Colavita (1992) noted that the Naval Observatory Prototype Interferometer (NPOI) on Anderson Mesa near Flagstaff, Arizona, and the CHARA Array could be equipped for narrow angle interferometric astrometry. We recognize that the potential exists to significantly modify the CHARA Array to accommodate dual beam interferometry. The feasibility and costs of this conversion have not been considered nor has the impact such a conversion would place upon the space available on Mt. Wilson for the central beam combining laboratory. We therefore point out only in passing that the potential does exists for the CHARA Array to carry out narrow angle interferometry as presently envisioned for the proposed Keck interferometer. We would essentially fill a gap between the Keck and the PTI capabilities. The major shortcoming of our facility over the Keck array, including its outriggers, is the decreased aperture. Thus, there would be fewer program stars with the minimum two faint reference stars available to us than at the Keck interferometer.

6. CONCLUSION

We have shown that the CHARA Array provides two relatively well understood and highly promising ways to contribute to the ASEPS undertaking: the detection of submotions in wide, relatively nearby binaries; and the imaging of protoplanetary structures such as gaps and rings in the disks surrounding young stellar objects. The former application requires no major modification of the baseline design for the Array, while the latter would benefit greatly from the addition of telescopes to provide expanded (u, v) coverage at moderate baselines. Two additional ASEPS applications include the imaging of microlensing events and the modification of the Array to perform narrow angle interferometry. Microlensing event imaging poses no engineering problems aside from pushing toward the limiting magnitude, however narrow angle interferometry would require extensive modification and expansion of our light collecting telescopes and beam combining facilities.

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