Science Objectives

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INTRODUCTION

In this appendix, we recapitulate and expand on the scientific opportunities discussed in the main body of the proposal. An analysis has been carried out in an attempt to assign a figure of merit to selected target programs in order to define a primary scientific program for the Array.

A.1. STELLAR ASTROPHYSICS – SINGLE STARS

A.1.1. Emergent Fluxes and Effective Temperatures

These quantities are determined from angular diameter measurements using the relations:

$$F \;=\; 4f/\Theta^2 \;=\; \sigma T_{eff}^4, \tag{A.1}$$

where F is the emergent flux at the stellar surface, f is the flux integrated over the photosphere as determined from absolute photometry, Θ is the measured angular diameter, σ is the Stefan-Boltzmann constant, and T_{eff} is the effective temperature. Θ is measured through a fit to the “visibility” or correlation curve given by

$$\left|V_1(b)\right| \;=\; \frac{(I_{max} - I_{min})}{(I_{max} + I_{min})} \;=\; \frac{2J_1(\pi\Theta b/\lambda)}{\pi\Theta b/\lambda}, \tag{A.2}$$

where J_1 is the first-order Bessel function, b is the interferometer baseline separating the two telescopes as projected onto the sky, and λ is the mean wavelength of the observation. The determination of Θ is thus a single parameter fit to a carefully calibrated measure of $|V_1(b)|$. T_{eff} is one of the fundamental astrophysical parameters characterizing stars, and the accurate determination of T_{eff}'s has been the classical primary goal of interferometry.

- To be of the greatest astrophysical use, Θ should be determined to an accuracy of better than 2% for significant samples of stars.
- Establish accurate T_{eff} scales within a grid of MK types, metallicities, rotational velocities, etc.
- All spectral types and luminosity classes are available with the most difficult being the hottest and coolest stars.
- Because limb-darkening is less in the near-IR, diameters are less subject to uncertainties when measured from single parameter visibility observations at those λ's.
- The calibration of flux sensitive photometric parameters such as $c_\circ$ is a significant goal.
- Wavelength dependence of apparent angular diameter for stars of various spectral types.

A.1.2. Photospheric Limb Darkening

This phenomenon results from the projected optical depth effects when a photosphere is viewed at increasing distances from the center. Under the simplifying assumptions of plane-parallel atmospheres, isotropic scattering and gray opacities, limb darkening follows a $cos\ \phi$ law, where $\mu \equiv cos\ \phi$. Thus, from center ($\mu = 0$) to edge ($\mu = 1$), limb darkening at optical depth 0 is given by:

$$I(\mu, 0) = I(1, 0)\frac{3}{5}\left(\mu + \frac{2}{3}\right). \tag{A.3}$$

The exact behavior of limb darkening provides insight into stellar atmospheres theory. The angular diameter Θ determined from the single parameter fit to $|V_1(b)|$ described above assumes a uniformly illuminated disk. The observational measurement of limb darkening is determined from the behavior of the visibility curve beyond the first null, and is thus a second order effect over the measurement of Θ. It is best carried out at visible wavelengths.

A.1.3. Linear Diameters

For stars of known parallax Π (in arcseconds), the linear diameter D of a star is given by:

$$D(km) \ = \ 1.5 \times 10^8 d\Theta \ = \ 1.5 \times 10^8 \Theta/\Pi, \tag{A.4}$$

where the distance d in parsecs is given by $d \ = \ 1/\Pi$. Stellar radius is related to mass by

$$R \ = \ \alpha M^{\beta} \tag{A.5}$$

where $\alpha = 1$ for R and M normalized to solar values and $\beta \sim 0.7$ for main sequence stars. The $R(M)$ relation has heretofore been based upon studies of eclipsing binaries in which proximity effects may bias the relation over what might be exhibited by single stars. The advent of accurate parallaxes from the HIPPARCOS astrometry satellite and from the USNO ground-based programs opens up the possibility of a reassessment of this fundamental relation in astrophysics.

A.1.4. Star Forming Regions

Moderate resolution in the far infrared is the most promising approach in looking for the complex structures that are expected to be associated with star formation. These regions are often heavily obscured by dust.

A.1.5. Pre-Main Sequence Objects

Structures associated with Pre-MS objects are of great interest, and require imaging at IR wavelengths at moderate to high resolution.

A.1.6. Young Stellar Objects

Dyck & Kibblewhite (1986) give a typical M magnitude of 1.9 and a diameter of 16 mas.

A.1.7. Rotation

Rotationally induced oblateness can amount to a 3 to 2 ratio of equatorial to polar diameter before breakup, and such extremes are expected on the basis of spectroscopic analyses. Ridgway (1989) mentions specifically FU Ori stars, two of which have K magnitudes of 4.9 and 5.8 respectively, and have equatorial/ polar diameters of about 2.0/ 0.2 mas. Experiments in differential techniques to determine the axis of a rotating main sequence star can be better done in the visual.

A.1.8. Reddened Stars

Observations of the diameters of heavily reddened M supergiants could provide better mapping of the galactic structure. At 2 kpc, a star like α Ori would have $E_v = 3.8$ and its energy distribution would peak at 1.6 um, rather than 0.9 um. Dyck & Kibblewhite (1986) note a list of 63 M supergiant stars with a median diameter of 2.8 mas, which have a magnitude of about 2.0 in K.

A.1.9. Flare Stars

The physical mechanisms for this phenominum are unknown. Are they associated with binaries? Do dust shells exist? Because time resolution of 5 min would be needed, measurements would be in "snapshot" mode. There are some 15 UV Cet flare stars with $V \leq 10$ and $K \leq 7$, but the diameters are less than 0.1 mas, out of feasible range in the near-IR. Therefore, only fairly hot dust shells could be measured.

A.1.10. Calibration of Cepheid P–L relation

The ESO/VLT Committee point out that an accuracy of 2% in the mean angular diameter of 29 Cepheids would decrease the 0.2 mag uncertainty in the P-L relation to 0.1 mag. It is not obvious what advantages near-IR would have over visual for this project, except that diameters may be better determined for the stars that are resolvable. The nearest Cepheids have diameters of 2 mas, just resolvable at 400 m (resolution at 2.2 um is 1.4 mas).

A.1.11. Pulsation Properties of Mira-type Long-Period Variables

There are roughly 20 Miras (LPV's) with K brighter than 2 and diameters larger than 5 mas. In particular nodal oscillations of LPV's could be determined by spatial interferometry (in conjunction with precision spectroscopy). Dyck & Kibblewhite (1986) mention a list of 49 Miras with T_{eff} in the range 2300–3100 K, which have a median diameter of 5.7 mas and median magnitude of 0.0 in K, translated into K magnitude from the M-band fluxes given by Dyck & Kibblewhite (1986). It appears that these objects would be well observed.

A.1.12. Surface Inhomogeneities

- Starspots on RS CVn stars requires $\leq$0.2 mas imaging and would be enhanced by spatially resolved Zeeman splitting observations.

- Detailed features on giants and supergiants to answer such questions as the role of chromospheric prominences vs. photospheric convection. ("Betelgeusean Astrophysics") In the K band for a 400 m baseline, α Ori would have about 46 resolution elements across the disk, or 1700 total resolution elements. The magnitude is about -5.0 in K, or about 3.1 per resolution element [the same for any star of this type]. One important question, given that many of these M stars have similar temperatures, is how filled does our dilute aperture have to be? If it is too dilute, we will not be able to recover useful images in a reasonable time. One major astrophysical question is how big are the turbulent eddies of stars of this type. It seems reasonable to suppose that the near-IR band is relatively better for observing stars of this class than the visual.

- Surface structures of stars of all MK types
- Imaging in Zeeman sensitive lines as a first direct measure of stellar magnetic field strengths plays an important role in the "solar-stellar connection".

A.1.13. P-mode Oscillations

Obtained via complementary high-resolution spectroscopy by observing in and out of selected lines.

A.1.14. Wolf-Rayet Stars

The diameter measurements of these hot objects could be done in the visual. IR speckle measurements of several objects [WC8-9 Ve 2-45, Dyck et al. (1984)] noted shells up to 250 mas in diameter at 2 um. Ridgeway mentions a target list of 41 Pop I W-R stars with median K $\leq$ 6.

A.1.15. Cool Evolved Stars with Dust Shells

Dyck & Kibblewhite (1986) note 63 cool stars with dense shells having median diameter of 25 mas, median M magnitude of -0.3. Temperature estimates are needed to calculate K magnitudes. These features can still be observed in K, but would be better in the thermal IR.

A.1.16. Novae & Supernovae as Targets of Opportunity

The temporal evolution of the rapidly expanding ejected material would be the primary scientific goal.

A.2. STELLAR ASTROPHYSICS – BINARY & MULTIPLE STARS

A.2.1. Masses

The masses of stars are of fundamental significance to stellar astrophysics through "Vogt's Theorem" which states that the entire course of evolution of a star is determined *a priori* by its initial mass and its initial chemical composition. Stellar masses are determinable only from binary star orbital motion studies through the application of Kepler's Third Law

$$(M_1 + M_2) \;=\; a^3/P^2, \tag{A.6}$$

where M_1 and M_2 are the mass (in units of solar masses) of the primary and secondary stars of a binary system, a is the orbital semimajor axis (expressed in AU), and P is the orbital period of revolution (expressed in years). The orbital elements a and P, along with six additional elements, are determined from a set of measurements of the angular separation ρ between component stars and the position angle θ, which specifies the relative orientation of the components, as a function of time t. Thus the basic observational material consists of sets of data (θ,ρ,t) obtained through single parameter fits of visibility curves, i.e. a binary star is resolved essentially through the detection of the first null in visibility by a multi-parameter fit to the visibility curve given by:

$$|V(b)|^2 \;=\; \frac{1}{(1+\beta)^2}\left[\beta^2|V_1(b)|^2 + |V_2(b)|^2 + 2\beta|V_1(b)||V_2(b)|cos\left\{\frac{2\pi b}{\lambda}\rho\ cos\psi\right\}\right], \qquad \text{(A.7)}$$

where β is the brightness ratio of the two stars (where $\beta \geq 1$), $|V_{1,2}(b)|$ are the visibility contributions arising from the individually resolved disks of the two stars (the subscript 1 refers to the "primary" or brighter star while the subscript 2 refers to the "secondary" or fainter component), $\rho\ cos\psi$ is the projection of the angular separation of the two stars onto the interferometer baseline with ψ being the angle in the plane of the sky between the position angle vector direction (determined by θ) and the projected interferometer baseline. The shape of the visibility curve for a binary is thus modified according to whether or not either or both of the two components are themselves resolved into disks.

- Accurate mass determinations exist for fewer than 100 systems whereas thousands of binaries are known.
- The $L(M)$ and $M(R)$ relations are currently completely insensitive to effects of evolution, metallicity, core rotation, etc.
- Almost no mass data exists for Pop II stars and highly evolved disk population stars.

A.2.2. Double-lined Spectroscopic Binaries

The direct resolution of DSB's results in a complete determination of the individual masses *and* in a geometrically determined *orbital parallax.* These values then lead to fundamentally determined masses and luminosities for the individual components providing that the value of Δm is also extracted from the interferometry. This is the most important class of binary for interferometry. Considered here is a set of 180 "guaranteed" objects whose angular separations are predicted to be $\geq$1 mas.

A.2.3. Single-lined Spectroscopic Binaries

Some 70% of the SB's in the Batten et al. *Eighth Catalogue...*, i.e. some 1,000 systems (distributed over the entire sky) have predicted $\rho \geq 0.2$ mas. The northern hemisphere is preferred for historical reasons. Many of the SSB's in this sample will be converted to DSB's through improved radial velocity techniques, and many will have accurate parallaxes from modern astrometry programs. Thus this is the second priority sample for mass determinations.

A.2.4. Astrophysics of Close Binaries

These objects are invariably SB's and often eclipsing binaries as well. The associated phenomena are: tidal distortion; mass exchange; circumstellar/circumsystem streams, shells, and disks; systemic mass loss; "reflection" effect; apsidal rotation; Roche lobe induced photospheric distortions, etc. Such effects will undoubtedly require very high resolution imaging. The imaging of an X-ray binary would reveal structures of accretion disks and tidal distortion mappings could lead to the definitive detection of the black hole and determination of its mass. This is an extremely challenging area.

A.2.5. Duplicity/Multiplicity Surveys

The frequency of this phenomenon is of fundamental significance to all areas of stellar astronomy ranging from the details of star formation to the frequency of life in the Universe. Surveys have heretofore been hampered by the limited sensitivity any particular technique has to detection, and interferometry will provide several decades of spatial resolution sensitivity. This will provide unprecedented completeness to surveys. New masses and luminosities will also result from newly discovered binaries that then become DSB's. Surveys should be conducted among broad samples of field stars delineated as to MK type, metallicity, rotation rate, abnormal spectral characteristics, etc.

A.2.6. Distance Calibrations

These result from resolution of DSB's (i.e. from determining orbital parallaxes) but are mentioned separately because of their specific significance. Resolution of cluster DSB's and field DSB's are possible out to distances of 10 kpc for a 400 m baseline thus offering new direct calibration of the galactic and extragalactic distance scales. Resolution of DSB's in the Magellanic Clouds might be feasible for a southern interferometer.

A.2.7. Low-Mass Companions

Cool stars, brown dwarfs and planets can be sought through the detection of submotions in the orbital motions of binaries if such a component exists in orbit about one component of a resolved binary. Here accuracy, rather than high resolution, is the key. The amplitude of the submotion is inversely proportional to the system's distance from the sun. Observations of high order visibility nulls may yield 100 μarcsec accuracy.

A.3. STAR CLUSTERS

A.3.1. Proper Motions Within Globular Clusters

This is an application of differential astrometry of closely spaced cluster members, completely analogous to the binary star problem.

A.3.2. Duplicity & Multiplicity of Cluster Members

Applicable to both galactic and globular star clusters, the problems described above in Section A.2 would be pursued within the cluster environment. Of special interest would be the direct measurement of cluster distances through the resolution of DSB's, the relative frequency of occurence of duplicity and multiplicity in clusters as opposed to field stars, and the comparison of cluster $L(M)$ and $R(M)$ relations compared to those of field stars.

A.4. EXTRAGALACTIC ASTRONOMY

A.4.1. Stellar Astrophysics Extrapolated to the Magellanic Clouds

This task is obviously deferred to a southern interferometric array, but could provide significant returns in many fields if sufficient magnitude sensitivity were available. At the distance of the Clouds, a limiting angular resolution of 0.2 mas corresponds to ~6 AU. The resolution of DSB's in the Clouds would result in the direct determination of the distance to the Magellanic Clouds. With a distance modulus of $m - M = +20$, the hottest main sequence stars would still be fainter than $m_v = +15$.

A.4.2. Imaging of Narrow and Broad Line Emission Regions in Active Galactic Nuclei

Even the brightest AGN places severe demands upon limiting sensitivity, and it is likely that K-band observations down to K = +16 would provide great returns assuming compensated imaging can be achieved. Baselines of several hundred meters would enable the imaging of core related features, including jets, for a number of AGNs. Narrow-line emission regions are thought to originate in structures several hundred parsecs in diameters while broad-line emission regions, while brighter in many cases, are associated with regions only 0.01 parsec in diameter corresponding to angular sizes of 10^{-8} arcsec at a distance of 1 megaparsec. The structure of the narrow-line regions and the multiplicity of otherwise unresolved broad-line sources are projects of high significance.

A.5. SOLAR SYSTEM ASTRONOMY

A.5.1. Minor Planets

Ridgeway (1989) lists 585 objects with $m_v \leq 11.0$ and $m_k \leq 10.0$ with diameters ≥ 8 mas. The near-IR is not very favorable for observations, due to the coolness of these objects. Minor planets may also be observed in the 3.0 um hydration band. Visibility related observations can lead to diameters, shapes and perhaps tomographically reconstructed images. Full scale imaging of low surface brightness objects is a challenge which may also stress field-of-view constraints.

A.5.2. Planetary Satellites

Dyke & Kibblewhite (1986) show that the spatial detection of Io's volcanos require a resolution of 12 mas, and a flux of 3.5 x $10^{-18} w/cm^2 \mu m$ at 5 μm. [i.e. $M_M = 6.6$.] These features have T = 600 K, and therefore will be difficult to observe in the near-IR.

A.5.3. Comets

These would be targets of opportunity with highly variable observational circumstances

A.5.4. Imaging of the Solar Surface

This highly specialized application superficially benefits from high photon flux, although requirements for very narrow line imaging quickly leads to photon starved situations as in nighttime interferometry. Baselines longer than ~5 m are not useful because of mean-free path considerations for photons in the solar atmosphere. New interest is arising among the solar physics community for a solar interferometer, but that instrument would be very different from the CHARA Array.

A.5.5. Detection of Other Planetary Systems

This application is pursuable along two lines:

- The direct IR detection of protoplanetary disks surrounding young stellar objects, and
- The astrometric detection of massive planets through submotions in binary systems as described in B.7.

A.6. SCIENCE CHARACTERIZATION PARAMETERS

In the table which follows, the Science Objectives listed in Sections A.5.1 through A.5.5 are characterized and quantified according to the parameters described below.

N $\equiv$ Logarithm of the Number of Objects in this Class

$\lambda_\circ$ $\equiv$ Optimum Wavelength Regime

  1 = Near infrared wavelengths (0.9 – 3.0 μm)
  2 = Visible wavelengths (0.4 – 0.9 μm)
  3 = Far infrared wavelengths ($\geq$3.0 μm)

M $\equiv$ Median Magnitude at $\lambda_\circ$ (V or K magnitude) of the Sample

  1 = Brighter than +6
  2 = Brighter than +11
  3 = Fainter than +11

S $\equiv$ Angular Size

  1 = 1–5 resolution elements
  2 = 5–25 resolution elements
  3 = $\geq$ 25 resolution elements

T $\equiv$ Integration Time Limitation

  1 = Diurnal restrictions only
  2 = $\leq$1 hour
  3 = $\leq$1 minute

C $\equiv$ Complexity Parameter

  1 = Single parameter fit to visibility
  2 = Multi-parameter (2-4) fit to visibility
  3 = Many-parameter ($\geq$5) fit to visibility
  4 = Complex extended object requiring full reconstructive imaging

TABLE A.1. Science Characterization Parameters

		N	λ_o	M	S	T	C	F	P	Q
1. Single Stars										
1.1	*F and* T_{eff}	4	2	2	1	1	1	1.3	1	1.1
1.2	$I(\mu, 0)$	3	2	2	1	1	2	1.7	2	1.9
1.3	*Linear Diameters*	2	2	2	1	1	1	1.3	2	1.8
1.4	*Star Forming Regions*	2	3	1	2	1	2-4	2.2	1	1.4
1.5	*Pre-MS Objects*	2	3	1	2	1	2-4	2.2	1	1.4
1.6	*YSOs*	2	1	1	1-2	1	2-3	1.6	1	1.2
1.7	*Rotation*	2	2	2	1	1	1	1.3	2	1.8
1.8	*Reddened Stars*	2	1	1	1	1	1	1.0	2	1.7
1.9	*Flare Stars*	1	2	2	1	1-2	3-4	2.3	2	2.1
1.10	*P–L relation*	2	2	2	1	2	1	1.5	1	2.3
1.11	*Long-Period Variables*	1	1-2	1	1-2	1	1	1.2	2	1.7
1.12	*Surface Structures*	2	1-2	1	1-2	1	3-4	2.0	1	1.3
1.13	*P-mode Oscillations*	2	2	1	1	2-3	1	1.4	2	1.8
1.14	*Wolf-Rayet stars*	2	2	2	1	1	1-3	1.7	2	1.9
1.15	*Dust Shells*	2	1	1	2-3	1	3-4	2.1	2	2.0
1.16	*Novae & Supernovae*	0	1-2	1	2-3	2-3	1-4	1.9	1	1.3
2. Binary & Multiple Stars										
2.1	*Masses*	3	2	1-2	1	1	2	1.6	1	1.2
2.2	*Double-lined SBs*	2	2	1	1	1	2	1.5	1	1.2
2.3	*Single-lined SBs*	3	2	1	1	1	2	1.5	2	1.8
2.4	*Close Binaries*	2	2	1	1	1	4	2.2	2	2.1
2.5	*Duplicity Surveys*	4	1-2	2	1	1	2	1.6	2	1.9
2.6	*Distance Calibrations*	1	2	2	1	1	2	1.7	1	1.2
2.7	*Low-Mass Companions*	2	2	1	1	1	2	1.5	1	1.2
3. Star Clusters										
3.1	*Proper Motions*	2	2	2	3	1	2	2.0	3	2.7
3.2	*Duplicity Surveys*	3	1-2	3	1-2	1-3	2-4	2.3	3	2.8
4. Extragalactic Astronomy										
4.1	*Magellanic Cloud Studies*	2	1-3	3	1-3	1-3	1-4	2.3	1	1.4
4.2	*Structure of AGNs*	2	1-2	3	1-2	1-3	2-4	2.3	1	1.4
5. Solar System Astronomy										
5.1	*Minor Planets*	2	2	2	3	2-3	4	2.9	2	2.3
5.2	*Planetary Satellites*	2	1-3	2	3	2-3	4	2.9	2	2.3
5.3	*Comets*	0	1-3	2	3	2-3	4	2.9	2	2.3
5.4	*Solar Surface Features*	3	2	2	3	2-3	4	2.9	2	2.3
5.5	*Extra-Solar Planets*	2	1-3	2	2	1	2	1.8	1	1.3

F $\equiv$ Feasibility = $(\lambda_\circ + \mathrm{M} + \mathrm{S} + \mathrm{T} + 2\mathrm{C})/6$

  1 = Highly feasible, essentially straightforward
  2 = Moderately difficult
  3 = Very difficult

P $\equiv$ Priority (Significance of Scientific Return)

  1 = Highest (of greatest scientific significance to many fields)
  2 = Moderate (of high, but more restricted significance)
  3 = Lower

Q $\equiv$ Figure of Overall Merit = $(\mathrm{F} + 2\mathrm{P})/3$

A.7. REFERENCES

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