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The Potential of Long–Baseline Optical Interferometry of Binary Stars

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ABSTRACT: Interferometric arrays possessing sub-milliarcsecond resolution are either about to be fully scientifically productive, as in the case of the Sydney University Stellar Interferometer, or are under various stages of planning and development. The 1990's will thus witness a hundred–fold gain in resolution over speckle interferometry at the largest telescopes and 5,000 times the resolution of classical direct imaging. Where speckle interferometry can now resolve binary stars with periods of 1 to 2 years, interferometric arrays with baselines of hundreds of meters will resolve binaries with periods of a few hours. Arrays will resolve the majority of the known spectroscopic binaries, providing a substantial increase in the quantity *and* quality of stellar mass determinations. Surveys for new binaries among the field stars and other restricted samples will be accomplished with unprecedented completeness. The remarkable enhancement in resolution we are about to witness from facilities like SUSI and our own proposed CHARA Array will quite literally revolutionize the field of double and multiple star research.

1. INTRODUCTION

Binary star studies provide the only direct means for measuring stellar masses. Although Vogt's Theorem is complicated by such phenomena as rotation and mass exchange in close binaries, the mass remains the single most important parameter in understanding a star's place within the theoretical framework of stellar evolution. Visual, photometric, and spectroscopic studies of binary star systems have continued in earnest since the late nineteenth century, but the collection of accurately determined masses remains remarkably meager. This situation is due to the fact that no single technique can furnish the complete set of information demanded by Kepler's Third Law for the determination of individual masses. Only by combining approaches — spectroscopy with photometry and micrometry with astrometry for the most part — has this restricted sample of fundamental data been painstakingly obtained. A major drawback is the tendency for selection effects of various methods to point in opposite directions and thus to discourage overlap. This has prevented the vast majority of known binary systems from contributing to the empirical mass–luminosity and mass–radius relations.

The current status of the empirical mass–luminosity relation is described by Popper (1980, 1985), Heintz (1985), and Andersen (1991). Heintz points out that the sample of visual binaries amenable to mass determinations, i.e. systems with reliable parallaxes and mass ratios, amounts to fewer than 50 systems out of the nearly 90,000 known pairs. The possibilities for dramatically increasing this collection are quite slim. For visual systems and for spectroscopic/eclipsing pairs, we can only expect gradual improvements in the number of new mass determinations and in the refinement of those that already exist. By basing the empirical relations upon systems with uncertainties as large as $\pm$ 15%, we lose sensitivity to fine structure expected from differing metallicity, core rotation, and the natural dispersion resulting from main sequence evolution. Stellar seismology offers an exciting probe of core rotation rates and their possibly significant influence on a star's placement on these fundamental relations. There are essentially no masses known for extreme metal–poor stars and only the barest of data pertaining to highly evolved, disk population stars. This sensitivity of mass to semimajor axis carries through to the luminosity being proportional to a^7 and the rate of evolution to a^6. Contemporary astrophysics will benefit tremendously from increases in the quantity and quality of fundamentally determined stellar masses. The key to this progress is in developing techniques which eliminate the isolation of selection effects inherent in current methods of binary star observation.

Speckle interferometry has significantly decreased the gap between visual and spectroscopic binaries by achieving resolutions down to 25 mas. Several dozen spectroscopic binaries with periods of the order of hundreds of days or longer have been resolved for the first time. Radial velocity studies of such systems are difficult due to velocity amplitudes of only a few kilometers per second, and hence highly accurate masses for most of these speckle–spectroscopic binaries may remain elusive. Speckle interferometry has shown the benefits high angular resolution brings to double star astronomy and tantalizingly points to what can be done with even higher resolution. Speckle programs are likely to make their most important contributions through very accurate measurement of close visual pairs and by determining the magnitudes and colors of individual components of systems having separations down to the diffraction limits of large telescopes.

While speckle interferometry has definitely enhanced the potential of binary star astrometry, long–baseline arrays will quite literally revolutionize the field. The success of the Mark III Interferometer in resolving systems with separations down to a few milliarcseconds (mas) has been dramatically demonstrated by contributors to this Colloquium. For the purposes of this discussion, we will consider the capability of a multiple-telescope array operating at visible wavelegnths and possessing a maximum baseline of 350 m. Such an array would have a limiting resolution for binary star studies of $\sim$0.16 mas. (This is precisely the resolution specification of the CHARA Array, described in a bit more detail in Section 6 below.) Simple inspection of Kepler's Third Law shows that, for a given distance, an increase in limiting resolution from 25 mas as in the case of speckle interferometry at a 4-m telescope to the 0.16 mas limit for the interferometer results in a gain in sensitivity to shorter periods by a factor $(25/0.16)^{3/2}$ = 1,950. Where speckle interferometry now resolves systems having periods of years, the array considered here will resolve binaries having periods of hours! A $2\mathcal{M}_\odot$ binary at 100 pc could be resolved if its period exceeds 12 hours, equivalent to a semimajor axis of only 0.016 A.U. A system of the same mass could be resolved from 1000 pc with a period as short as 16 days.

It is important to point out that 2-d coverage of binary star motion is required to determine the orbital inclination. Interferometers that rely simply upon Earth rotation to supply some 2-d u-v coverage will have difficulty in unambiguously determining inclinations for binaries found near the celestial equator. At high declinations, such instruments will not achieve their full potential resolution due to the unequal sensitivities in perpendicular directions.

2. DIRECT RESOLUTION OF SPECTROSCOPIC BINARIES

Double–lined systems offer the most promising returns from binary star interferometry. These objects with small Δm's are most likely to be resolved, and the mass ratio and linear value of $a \sin i$ are known. The combination of angular separations with the linear parameters from the radial velocities determines the distance to a system. The interferometrically determined inclination then provides the missing information to yield the masses of both components. Luminosities *and* masses of the individual components of double–lined binaries can thus be fundamentally determined. None of these quantities can be derived from either set of observations alone. Systems with unequal components provide a critical test of stellar evolution theory by the requirement that the two physically dissimilar stars must fit a single isochrone. Arrays can resolve the individual photospheres of one or both components in many of these systems to yield masses, absolute radii, and luminosities. For the first time, the prospect exists of directly and accurately measuring *all* of the basic astrophysical parameters for a substantial collection of stars. Such complete knowledge has to date been determined only in the case of the Narrabri results for Spica (Herbison–Evans *et al.* 1971).

Distances determined in this manner are independent of interstellar extinction (and hence can be used to probe the interstellar medium) and can penetrate far beyond the effective limit for parallaxes while preserving the directness and uniqueness of simple geometry. Resolution of spectroscopic binaries in the Hyades, Pleiades, and Praesepe clusters and in more distant galactic clusters will yield accurate distance calibrations and provide further insight into cluster evolution. The array considered here could detect and resolve an early–type binary with a period of 1000 days out to 10 kpc to provide a significant step outward in directly determined extragalactic distances.

Single–lined binaries do not yield a complete set of orbital and physical parameters. If the trigonometric parallax is known and the apparent orbit is determined interferometrically, then the resulting mass sum can be combined with the spectroscopically determined mass function to give the individual masses. Improvements in instrumentation, signal–to–noise, and radial velocity algorithms have, in recent years, pushed back the boundary between double– and single–lined binaries, so that lines from both components with $\Delta m \leq 5$ mag have been precisely measured. Several examples of radial velocity programs producing new levels of precision have been described at this Colloquium.

By determining spectroscopic parallaxes for the systems in the *Seventh Catalogue of the Orbital Elements of Spectroscopic Binary Systems* of Batten *et al.* (1978), Halbwachs (1981) predicted angular separations at nodal passages, values representing minimum guaranteed separations independent of inclination. Of the 978 cataloged systems, 683 binaries or 70% of the entire sample are predicted to have $\rho \geq 0.2$ mas and are prime candidates for resolution. Some of these will, of course, be inaccessible to any particular interferometer due to unfavorable declinations. For historical reasons, an interferometer in the northern hemisphere has far greater access to these systems than a facility in the southern hemisphere.

By considering only double–lined systems as prime candidates because of their anticipated small Δm's and objects north of δ = -20° with $\rho \geq 1$ mas, 180 systems are essentially *guaranteed to be resolvable.* This is a very conservatively selected sample, because 1 mas is six times the limiting resolution envisioned here. Many more double–lined systems will actually be resolvable as will those additional single–lined systems that will be converted to double–lined status through complementary spectroscopic programs. Table 1 lists, as a function of MK spectral type, the numbers of individual stars having well determined masses according to Popper (1980) followed in parentheses by the number of *additional* stars whose masses are *guaranteed* to be determined from the 180 spectroscopic binaries that will be easily resolved by an interferometric array. This sample will not only broaden the main sequence coverage, except for the very hottest and very coolest stars, it will significantly expand the collection of accurately known masses to evolved stars.

TABLE 1. Stars of Accurately Known Mass

Spectral Class	Luminosity Class V	IV	III	II	I
O	4(0)	0(0)	0(1)	0(0)	0(1)
B	31(35)	0(3)	0(5)	0(0)	0(0)
A	18(61)	0(3)	0(5)	0(0)	0(0)
F	40(44)	0(11)	0(4)	0(1)	0(2)
G	7(12)	1(6)	2(12)	0(0)	0(1)
K	7(4)	0(4)	0(5)	0(2)	0(2)
M	14(0)	0(0)	0(1)	0(0)	0(1)

3. SURVEYS FOR NEW BINARIES

It is of great interest to better understand the frequency of occurrence of binaries. These statistics are fundamental to our picture of star formation and may even shed light on the question of the frequency of life in the Universe. Heterogeneous and poorly understood selection effects within and among the various binary star catalogs make them questionable sources for studying this apparently widespread phenomenon.

Long–baseline arrays finally bring to bear on this problem a technique with well–understood selection effects sensitive to four decades of orbital periods. The classical gap between visual and spectroscopic coverage is completely eliminated. A survey of carefully selected samples of stars using a restricted grid of baselines would provide new insights in only a few years.

Surveys are of interest for other than statistical purposes. Certain phenomena, particularly those associated with early–type stars, are often suggested to arise from duplicity. Spectroscopic detection of duplicity among these stars is impeded by the presence of relatively few, and often very broad, lines. Surveys of B and A stars would provide important constraints upon the now open ramifications of duplicity for these stars. Surveys of stars with spectrum peculiarities (such as the metallic–line stars and WR stars) are of considerable interest. A particularly intriguing class are the subdwarf B stars whose evolutionary status requires a theoretically difficult shedding of much of the star's mass in order to expose the He core. These stars might be binaries lying within a separation regime inaccessible to speckle interferometry, and may be related to the CH and Ba II stars, the latter class almost certainly being binary in nature. Finally, arrays would provide new, very powerful leverage in investigating duplicity frequencies of cluster stars in comparison to the field population and in a comparison of halo stars with the disk population.

4. RAMIFICATIONS FOR CLOSE BINARIES

Interferometer arrays, for the first time, permit the resolution of binary systems that exhibit the many complicated phenomena associated with "close" binaries. Such phenomena include tidal distortions, mass exchange, and the creation of circumstellar or circumsystem streams, shells, disks, and systemic mass loss, as well as other unique phenomena such as the "reflection effect". Thompson (1976) discussed these effects in the context of their influence on interferometrically measured parameters.

Algol is an example of one classic close binary resolvable by an array. At a distance of 30 pc, the 2.867–day system presents a 2.2 mas angular separation and could easily be resolved if the Δm between the B8 primary and late G or early K sub-giant secondary could be effectively diminished by observing in the near infrared. The photosphere of the primary star will also be resolvable, and the secondary star may be marginally resolved. The passage of the cool sub-giant across the disk of the hot star during primary eclipse could actually be "seen". Narrow–band observations would resolve emission features showing up at various orbital phases. Imaging algorithms employing closure phase or tomographic principles may be particularly useful here.

The determination of "visual" orbits for close binaries provides a means for directly measuring apsidal rotation rates by observing the apparent change in the position angle of the major axis of the orbit. This phenomenon has long been known to be a very sensitive indicator of the density gradients of the interiors of the component stars. It may even be possible to detect the relativistic component of apsidal motion. Furthermore, rapid core rotation has been suggested as a driving mechanism for the non-radial pulsations frequently observed in the atmospheres of hot stars. Arrays will provide a new capability for applying apsidal motion techniques for probing stellar interiors, thereby complementing and checking other methods.

5. THE DETECTION OF LOW–MASS COMPANIONS

Observations of widely separated binary systems provide a new means of searching for low–mass companions. It is not the high resolution but rather the high accuracy of the separation measures that enables the astrometric detection of companions of very low mass, including the regime of Jovian planetary masses. This application has been recently demonstrated by Cole *et al.* (1992) in the detection of a third companion in the CHARA speckle observations of the visual binary ADS 784. This new companion was confirmed by spectroscopy. The presence of planetary mass objects in detached binaries cannot be ruled out, and it has been shown by Harrington (1977) that a wide class of highly stable orbits can exist in such objects. Planet–forming disks may be unstable in pre-main–sequence binaries, and the information we have seen at this Colloquium concerning the frequency of binaries among pre-main sequence stars may have fascinating repurcussions on the frequency of planetary systems. With the theoretical uncertainties involved in these considerations and the tremendous scientific and popular interest in the presence of planets and brown dwarfs in the Galaxy, all efforts at detecting these bodies either alone or in physical association with single or multiple stars must be given high priority.

Arrays would be used in this application by measuring visibilities many cycles away from the first null. Speckle observations provide accurate input to restrict within a fraction of a cycle the precise null regime in which a given baseline is operating. Measurements from just a few baselines would provide a vernier–like improvement of the speckle measurement yielding accuracies at the 100 μarcsec level. Other extrasolar planet detection methods avoid binaries because of image and spectral line blending. Thus perhaps the majority of stars must otherwise be excluded from searches for other planetary systems.

6. THE CHARA ARRAY

The Center for High Angular Resolution Astronomy (CHARA) was established at GSU in 1984 with the goal of designing, constructing and operating a facility for very high spatial resolution astronomy. This goal grew out of a decade of activity in speckle interferometry using GSU instrumentation at the Kitt Peak 4-m telescope and at other large telescopes where speckle methods are ideally suited to the study of close "visual" binaries. Speckle methods provide important results for a variety of objects, but many pressing problems require resolution far beyond that which can be expected from single aperture telescopes. In early 1986, and with the support of the National Science Foundation, CHARA initiated a detailed exploration of the feasibility of constructing a facility with a 100–fold increase in angular resolution beyond the diffraction limits of the largest existing telescopes. In late November 1987, the Georgia Tech Research Institute joined with CHARA to continue and complete the design concept study. At the time of this Colloquium, we expect to receive funding from the NSF which will permit the GSU/GTRI partnership to proceed with the final development issues so as to permit construction of the Array to begin in 1994 or 1995. In this section, only a very brief overview of the CHARA Array project is given.

In the present design concept, the CHARA Array will consist of seven 1-m aperture collecting telescopes in a Y-shaped array enclosed by a 400-m diameter circle. Each telescope will be of alt/az design with an afocal optical system out of which a 20-cm diameter beam is relayed to a central station through an evacuated light pipe. This permits all seven beams to be simultaneously accessible. Each beam is fed to an optical path length equalization system containing a cat-seye optical arrangement driven along precise horzontal rails. The outputs are then fed to another stage of beam compression, again by a factor of five, before going to the final beam combination table where the interferometric combination of beams will be done in the pupil, rather than in the image plane.

An artists concept of the Array is shown in Figure 1. At the nominal

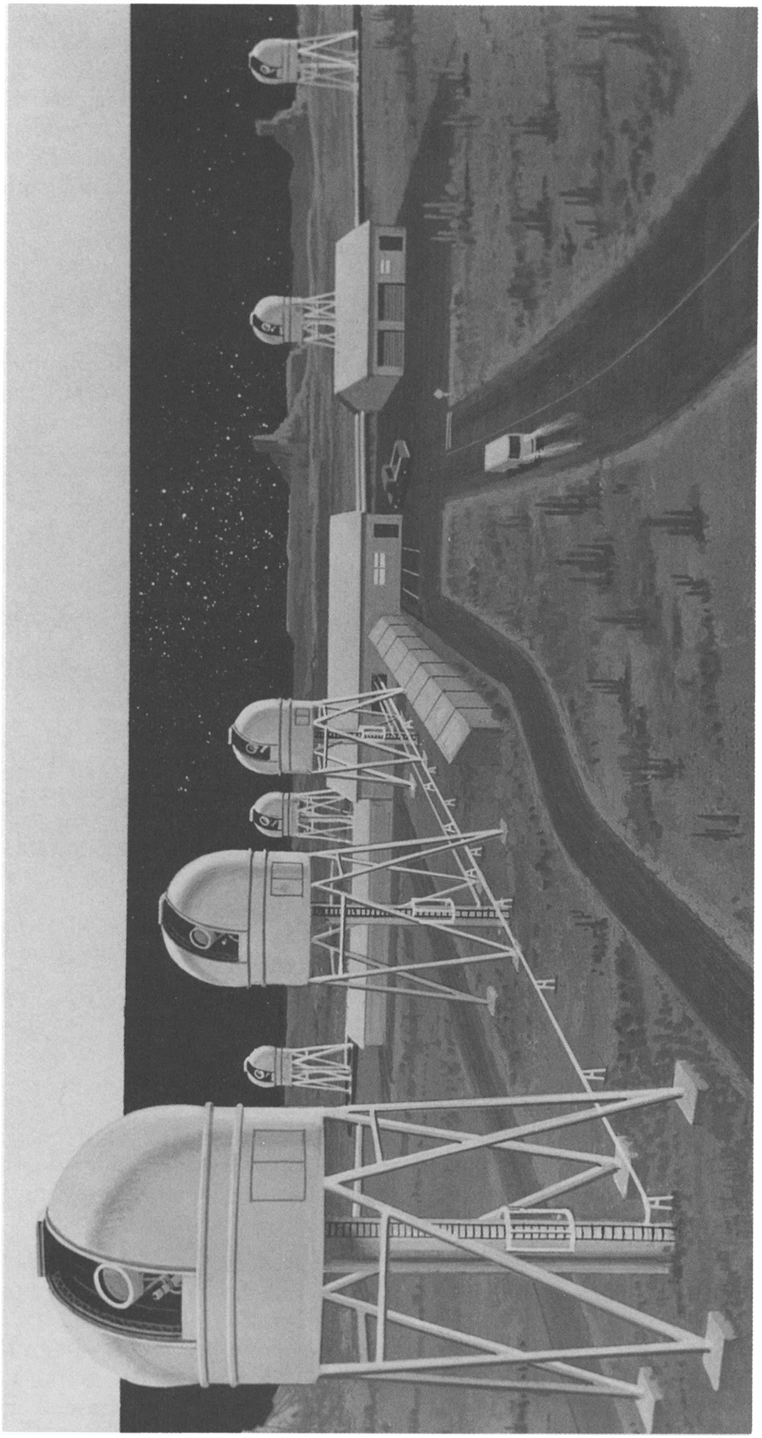

FIGURE 1. An artist's concept of the CHARA Array is shown above in which the seven 1-m telescopes direct their collimated beams to a central station for analysis. This painting originally appeared in the November 1989 issue of *Popular Mechanics*.

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operating wavelength of 550 nm, the Array will achieve limiting resolutions of 0.35 mas for single objects and 0.16 mas for binary stars. The CHARA Array will thus be ideally suited to embark upon the binary star programs described in the previous sections of this paper as well as upon a variety of programs of imaging at optical and infrared wavelengths. With the addition of adaptive optics, the Array would become a premier tool for very high resolution imaging across all fields of astronomy.

7. ACKNOWLEDGEMENTS

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9. DISCUSSION

WARREN: Does your estimated cost for the CHARA Array include adaptive optics; if not how much additional funding might the inclusion of adaptive optics involve, and how much will an infrared capability cost?

McALISTER: The cost estimate of $10.6M includes only a modest IR capability and no provision for adaptive optics, other than simple tilt correction. AO and the IR are extremely important to the realization of the full potential of long–baseline interferometry, and during our upcoming year of redefining the Array, both areas will receive much greater emphasis than previously given. The cost impact could be substantial, but I can't give a meaningful estimate of that impact yet.

QUIRRENBACH: You mentioned the importance of imaging for observations of close binaries. Do you consider the capability of reconfiguring the array, which would enhance the imaging capabilities?

McALISTER: Movable light collectors provides the most flexible way of filling in the (u,v) plane, especially at those frequencies which might be most critical to imaging. On the other hand, movable telescopes add a level of engineering complexity which is non-trivial. This is another area in which we plan to consider the tradeoffs during the coming year.

POPPER: Most interferometer have apertures approximately the isoplanatic patch. Without using a speckle technique, how do you compensate for the overlapping of many patch images from your large aperture telescopes?

McALISTER: The most straighforward approach is in the analysis of the pupil plane interferograms to treat the pupil as composed of many sub-pupils, each of which is adjusted to the seeing at the time of observations. We thus have a gain in limiting sensitivity provided by parallel processing of many r_o size patches. Adaptive optics is really what is needed here to realize the full potential of the aperture at visible wavelengths. In the IR, 1-m apertures will often represent a single r_o patch.

ISOBE: To expand baselines longer than 100 m, it becomes more difficult to keep coherence. How do you solve this difficulty?

McALISTER: Yes, there is a steady increase in difficulty, although I do not believe we yet know where a serious challenge to engineering sets in. I believe it is probably at baselines of 1 km or more. SUSI, with its 640-m baseline, will set a standard of difficulty here.

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