LONG BASELINE INTERFEROMETRY AND BINARY STARS

John Davis
Chatterton Astronomy Department, School of Physics, University of Sydney, Australia

ABSTRACT

The observations of α Vir with the Narrabri Stellar Intensity Interferometer demonstrated the potential of long baseline interferometry for the determination of fundamental properties of double-lined spectroscopic binary systems. Since the completion of the programme with the Narrabri instrument the Chatterton Astronomy Department has been conducting a study aimed at developing a stellar interferometer with limiting magnitude $V \gtrsim +8$ and maximum baseline $\gtrsim 1$ km (resolution at 500 nm $\lesssim 7 \times 10^{-5}$ seconds of arc). The way in which a long baseline interferometer may be used in the study of binary stars is outlined, the requirements for this work are discussed, and the current status and future plans of the Chatterton Astronomy Department's programme to develop a new long baseline interferometer are summarised.

1. INTRODUCTION

Observations of binary stars with an interferometer provide data which are complementary to those obtainable by other techniques. Combination of interferometric data with, for example, spectroscopic data, leads to a more complete knowledge of the fundamental physical parameters of a binary system. This is true for observations using a single aperture, as in speckle interferometry, or using two or more apertures, as in Michelson, intensity or "amplitude" interferometry. As implied by the title, the present discussion will be limited to interferometry involving apertures separated by baselines in excess of telescope aperture diameters.

The Chatterton Astronomy Department of the University of Sydney began its involvement in long baseline interferometry with the Narrabri Stellar Intensity Interferometer[1] which, apart from revealing a number of previously unsuspected binary stars in a programme of angular diameter measurements of single stars[2], was used for a detailed study of the double-lined spectroscopic binary α Vir[3]. This latter work clearly demonstrated that, for suitable double-lined spectroscopic binaries, interferometric observations enable the distance to the binary and the angular size of at least the primary, and hence the radius of the primary, to be calculated. The observation of this type of system also yields the masses of both components and the emergent flux, effective temperature and, in combination with the radius, the luminosity of at least the primary component. McAlister, in a review of the potential of high angular resolution interferometry for the study of binary stars[4], has suggested that the results for α Vir might "serve as a model of completeness for future combined interferometric, spectroscopic and photometric studies".

The programme of the Chatterton Astronomy Department is currently directed towards the development of a long baseline stellar interferometer of significantly higher sensitivity and resolution than the Narrabri instrument. The study of binary stars would be a major observational programme for such an instrument. This programme would provide fundamental determinations of mass, radius and effective temperature for individual component stars, accurate distances to binary systems beyond the reach of conventional trigonometric parallax measurements and it would have the

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potential to overcome the problems of non-overlapping selection effects involved in visual and spectroscopic binary star studies.

In this paper an outline is given of the way in which a long baseline interferometer may be used in the study of binary stars. The requirements for such an instrument are discussed and the current status of the Chatterton Astronomy Department's programme to develop a new long baseline interferometer is summarised.

2. METHOD OF OBSERVATION

In order to determine the brightness distribution across an object uniquely it is necessary to measure both the amplitude and phase of the complex degree of coherence over a wide range of spacings. In practice, interferometric determinations of angular diameters have been made by measurements of the square of the modulus of the complex degree of coherence or, in other words, the square of the fringe visibility V, whether by Michelson, intensity, speckle or "amplitude" interferometers. The consequent assumption of symmetry in brightness distributions is acceptable for most astronomical applications. In the case of a binary star, the lack of knowledge of the phase simply means that it is not possible to distinguish between certain mirror ambiguities in the orientation of the system. This is of no practical significance.

For a binary star, the response of an interferometer which measures the square of the fringe visibility V(d) at baseline (d) is given by[5]

$$V^2(d) = \frac{1}{(1+\beta)^2}\left[\beta^2 V_1{}^2(d) + V_2{}^2(d) + 2\beta V_1(d)V_2(d)\cos\left\{\frac{2\pi\theta_s d\cos\psi}{\lambda}\right\}\right] \quad \text{-- (1)}$$

$$\text{where } V_1(d) = \frac{2J_1(\pi\theta_1 d/\lambda)}{\pi\theta_1 d/\lambda}$$

$$V_2(d) = \frac{2J_1(\pi\theta_2 d/\lambda)}{\pi\theta_2 d/\lambda}$$

and λ is the wavelength of observation: θ_1 and θ_2 are the angular diameters (equivalent uniform discs) of the primary and secondary; β is the brightness ratio of the components ($\beta \geq 1$); θ_s is the angular separation of the components projected on to the plane of the sky; ψ is the angle in the plane of the sky between the projection of the line joining the stars and the baseline of the interferometer.

Equation (1) assumes that the mirrors of the interferometer are not large enough to significantly resolve either the discs of the stars or their angular separation. Partial resolution effects will generally be negligible but can be taken into account by including partial resolution factors[6] in equation (1).

The shape of the response given by equation (1) depends on the angular sizes of the components (θ_1 and θ_2), the brightness ratio (β) and the projected angular separation ($|\theta_s\cos\psi|$). It follows that observations with an interferometer can yield measurements of these parameters. Figures 1-3 show some typical examples of binary response curves and illustrate the effect of varying β, θ_2 and $|\theta_s\cos\psi|$ respectively.

In each case the angular size of the primary has been taken to be 1 millisecond of arc. The curves can be scaled to other angular sizes since, for a given value of $V^2(d)$, $d \propto 1/\theta$.

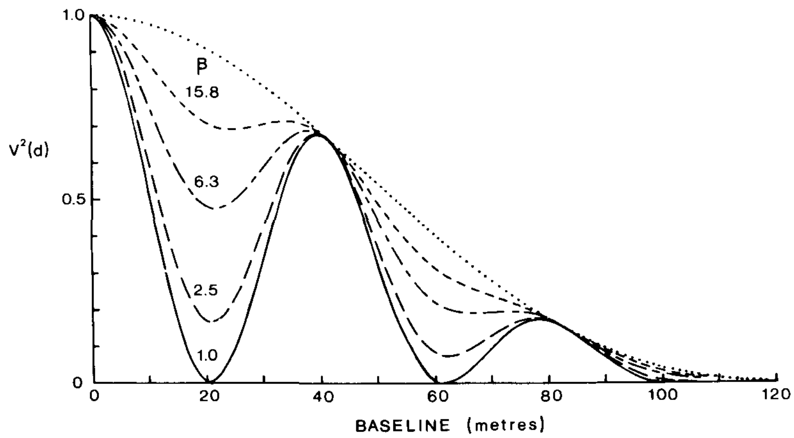

Figure 1. The response curves for a long baseline interferometer, which measures the square of the fringe visibility ($V^2(d)$) or its equivalent, to binary stars of different brightness ratios β (primary/secondary) for a wavelength of 500 nm. For each curve the angular diameters of both primary and secondary have been taken equal to 1 millisecond of arc and the projected angular separation to be constant at 2.5 milliseconds of arc. The dotted curve is the response to a single star with an angular diameter of 1 millisecond of arc.

Figure 1 shows the effect of changing the relative brightness of the two component stars while keeping their angular sizes equal ($\theta_1 = \theta_2$) and their projected angular separation constant ($\theta_s \cos\psi = 2.5\theta_1$). For reference the curve for a single star, with the same angular size as the components, has been included in Figure 1 and it is noted that this is also the response for the binary when the projection of the line joining the components is perpendicular to the baseline of the interferometer ($\cos\psi = 0$). For a binary star the response does not decrease steadily with baseline (except when $\cos\psi = 0$) but is modulated at a frequency determined by $|\theta_s \cos\psi|$ and with an amplitude which depends on the brightness ratio (β). The modulated curves in Figure 1 are drawn for values of β corresponding to magnitude differences between the components (Δm) of 0, 1, 2 and 3 magnitudes. For binaries with Δm less than 2 magnitudes, the depth of modulation, at the baseline for which $V^2(d) = 0.5$ for a single star, will be $>0.24V^2(0)$. This should be adequate for studying all double-lined spectroscopic binaries brighter than the sensitivity limit of a long baseline interferometer since they generally have $\Delta m \lesssim 2$ magnitudes.

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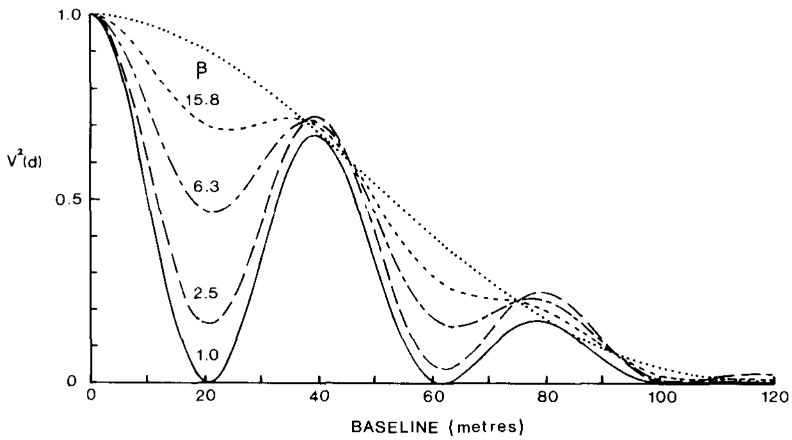

Figure 2. The same as Figure 1 with the angular size of the primary equal to 1 millisecond of arc but with the angular size of the secondary equal to $1/\sqrt{\beta}$ milliseconds of arc. The dotted curve is the response to a single star with an angular diameter of 1 millisecond of arc.

Figure 2 is similar to Figure 1 except that it shows the effect of varying the angular size of the secondary. For this purpose θ_2 has been put equal to $\theta_1/\sqrt{\beta}$. Again the curve for a single star, with the same angular size as the primary, has been included for reference. Comparison of Figures 1 and 2 shows that changing the size of the secondary has only a small effect, particularly for values of β much greater than unity. Thompson[7] has concluded that when the secondary is fainter and smaller than the primary, it is not possible to determine its angular size but, as was done in the study[3] of α Vir, a reasonable value for the angular diameter may be assumed in the analysis of long baseline interferometric observations with no significant effect on the determination of the angular size of the primary or the orbital parameters of the binary.

Figure 3 shows the effect of changing the projected angular separation of the components ($|\theta_s \cos\psi|$). For a binary system the projected separation varies with time due to orbital motion and also because of changes in the relative orientation of the baseline due to the rotation of the earth. Thus, for any given baseline d, the value $V^2(d)$ will vary with time. The depth of modulation, relative to $V^2(0)$, depends on β as shown by Figure 1, while the *observed* variation in $V^2(d)$ will also depend on the range and rates of variation in $|\theta_s \cos\psi|$ as can be deduced from Figure 3.

In considering the variation of $|\theta_s \cos\psi|$ it is important to distinguish between the variations in θ_s and ψ because the orbital elements can only be established uniquely if θ_s and ψ are *both* known over a significant fraction of an orbit. The variation in angular separation (θ_s) is due solely to orbital motion whereas the projection angle (ψ) varies due to orbital motion but may also vary as a result of changes in the relative orientation of the baseline. If the relative baseline orientation does not change it is impossible to distinguish between solutions for the orbital elements which have the same values of $|\theta_s \cos\psi|$ throughout their orbits[7]. Thus, it is necessary for the relative orientation of the baseline to change

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significantly during an observation if a unique solution for the orbital elements is to be found.

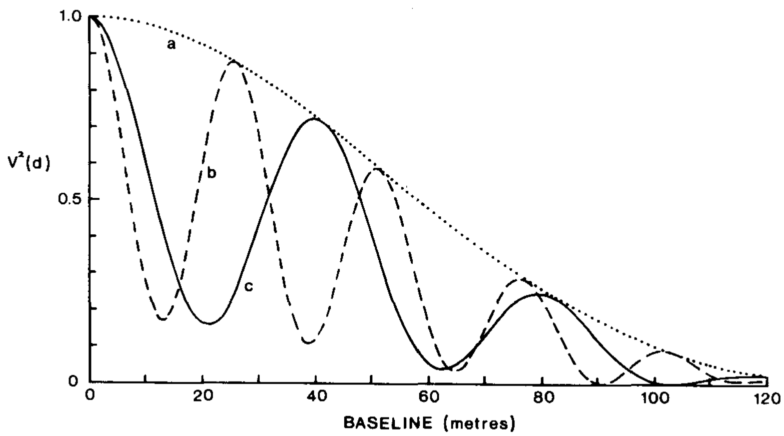

Figure 3. The response curves for a long baseline interferometer to a binary star with different projected angular separations $|\theta_s \cos\psi|$. For each curve the angular size of the primary has been taken equal to 1 millisecond of arc, the secondary equal to $1/\sqrt{\beta}$ milliseconds of arc, the brightness ratio β equal to 2.5 and the wavelength equal to 500 nm. For curve (a) $|\theta_s \cos\psi| = 0$, for curve (b) $|\theta_s \cos\psi| = 4$ milliseconds of arc, and for curve (c) $|\theta_s \cos\psi| = 2.5$ milliseconds of arc.

The change in relative orientation of the baseline or, in other words, the change in position angle of the projection of the baseline on the sky plane, due to the rotation of the earth, depends on the orientation of the baseline on the surface of the earth. For example, the changes in position angle as a function of declination, for an interferometer sited at latitude 30° South, are shown in Figure 4 for baselines oriented East-West, North-South and for a baseline that rotates in azimuth to be always perpendicular to the stellar azimuth as was the case for the Narrabri Stellar Interferometer[1]. In calculating the change in position angle it has been assumed that observations are restricted to elevations exceeding 30°.

The rotating baseline gives the largest range in position angle for all declinations and it has the advantage that it makes the matching of optical paths relatively easy. However, it is not practical for baselines greater than the order of 200 m for an intensity interferometer[8] or greater than a few metres for a Michelson or amplitude interferometer. In practice, for the rotating baseline, the range in position angle for declinations ∿ -30° (at latitude 30° South) would be less than shown since it is not possible to track close to the zenith with an azimuth mount, and a large fraction of the position angle change occurs in this region. For an interferometer with a fixed orientation baseline the East-West alignment is preferable to North-

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South because of the significantly better position angle range for declinations south of -15°. However, a combination of both East-West and North-South baselines would be highly desirable for binary studies because the position angle ranges add without overlap, except when the sum of the two ranges exceeds 180°.

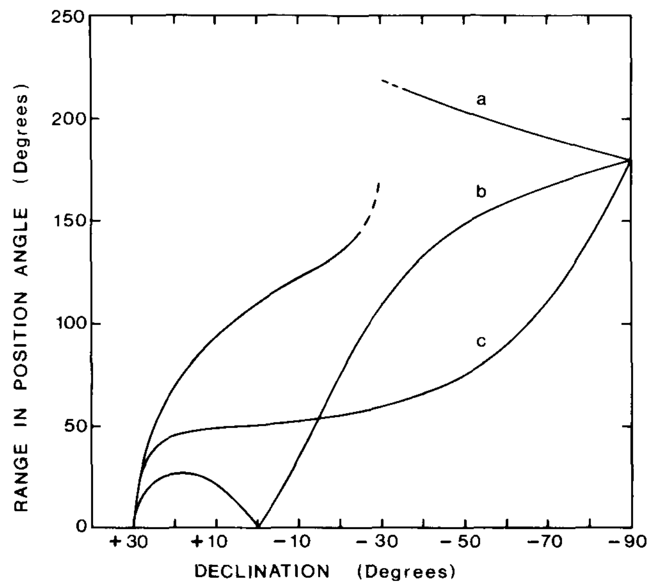

Figure 4. The change in position angle of the projection of the baseline of an interferometer on the sky plane due to the rotation of the earth. The diagram is for an interferometer sited at latitude 30° South and assumes observations are restricted to elevations exceeding 30°. Curve (a) is for a baseline that rotates in azimuth to remain perpendicular to the stellar azimuth, curve (b) is for an East-West baseline and curve (c) is for a North-South baseline.

The observations of a binary system with a long baseline interferometer would generally follow the approach adopted for α Vir[3]. $V^2(d)$, or its equivalent, would be measured over as great a range in position angle as possible, and for a number of baselines chosen to give the maximum variation in $V^2(d)$. Examples of the observed variation in the equivalent of $V^2(d)$ have been published[3] for α Vir. Analysis of the observational data would also follow the general approach adopted for α Vir[3,9] with a least-squares multi-parameter fit in which those parameters determined with superior accuracy from spectroscopic observations are fixed and the remaining "free" parameters are optimised.

3. SENSITIVITY AND RESOLUTION LIMITS

The instrumental requirements for the application of long baseline interferometry to single objects in the visual region of the spectrum have been reviewed in some detail by the author[10]. On the basis of this review, it was suggested that the targets for designers of future long baseline stellar interferometers should be V(limit) > +7; baselines of 200-300 m (> 1 km to resolve the hottest stars); and an accuracy of ≲ ± 2% in angular diameter measurements. It is not so easy to specify the instrumental requirements for the study of binary stars because of the influence of several factors including the brightness ratio, the orbital period, the projected angular size of the orbit and the range in position angle over which observations can be made. However, it is generally true that the requirements are similar to those for single star programmes except that a binary star needs to be brighter than the sensitivity limit of an interferometer for single stars if it is to be measured.

Thompson has discussed the sensitivity required for measuring a binary star[7] and concludes that a binary should be ∿ 1.5 magnitudes brighter than the limiting magnitude of an interferometer for single stars. This conclusion is supported by the experience gained with the Narrabri Intensity Interferometer observations of α Vir[3] which, with V = +0.99, was 1.5 magnitudes brighter than the sensitivity limit of that instrument.

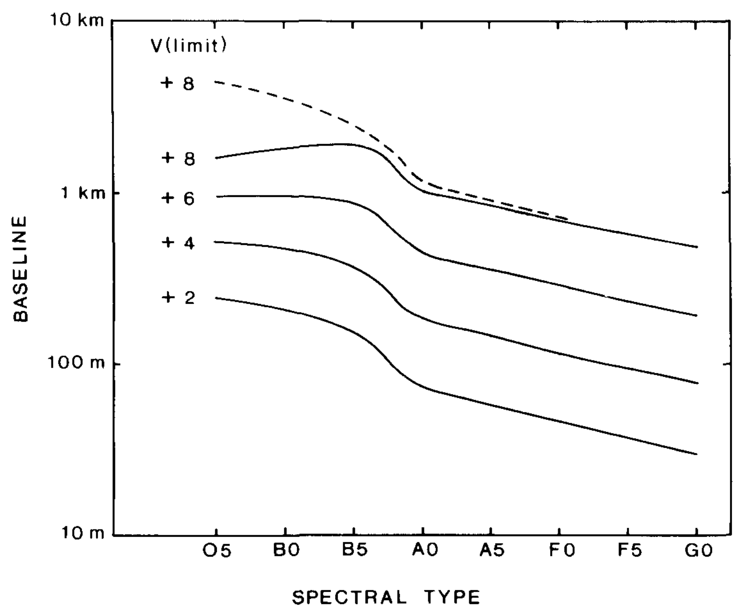

Figure 5. The baseline required to study a binary star as a function of spectral type for different limiting sensitivities and for a wavelength of 500 nm. The required baseline is assumed to be that for which $V^2(d) = 0.3$ for the primary component of the binary alone. V(limit) is the limiting magnitude for a binary star (see text) and an interstellar extinction of 0.8 magnitudes per kiloparsec[11] has been assumed. The broken curve corresponds to V(limit) = +8 magnitudes with no interstellar extinction.

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The question of the length of baseline required for the study of binary stars, given the limiting sensitivity of an interferometer, may be approached in more than one way. If the problem were simply to measure the orbital parameters one would choose a maximum baseline long enough to enable the full depth of modulation of the response curve to be observed. However, in the study of a binary with an interferometer, the aim would be to measure the angular diameter of the primary as well as the orbital parameters. The optimum baselines required for measuring the angular size of the primary corresponds to the point on the response curve, for the primary alone, where $V^2(d) \simeq 0.3$. This baseline will generally exceed that required for determining the orbital elements of the binary and will be adopted as the maximum baseline required for binary star studies.

Figure 5 shows the maximum baseline required for binary star studies, computed on the above basis assuming equal brightness components ($\beta = 1$), as a function of spectral type and for different limiting sensitivities. The figure is not intended to be definitive but simply to give an indication of the baselines required. In practice, the limiting sensitivity of an interferometer for single stars would be $\sim$ 1.5 magnitudes fainter than the V(limit) in Figure 5 and the maximum baseline required would be correspondingly longer. Thus, providing an interferometer can be made to work at these longer baselines, the requirements for binary studies lie within those for single star programmes.

4. LONG BASELINE INTERFEROMETERS

The targets for the designers of future stellar interferometers given in Section 3 might be reached either with a very large intensity interferometer or with a modern form of Michelson's interferometer employing large apertures as proposed by Labeyrie[12], or small apertures, as proposed by Twiss[13,14] and by Currie and his colleagues[15,16].

There is no doubt that a very large intensity interferometer could be built and that it would work. Indeed, a large stellar intensity interferometer was proposed in the early 1970s by Hanbury Brown and Davis[8,17] based on their experience with the Narrabri Intensity Interferometer. The Australian Government awarded a design study grant but a detailed reappraisal of the proposal, based on advances made in several related areas during the period that the proposal was being considered by the Government, led to the conclusion that a "modern" Michelson interferometer offered the possibility of greater sensitivity at lower cost[18].

The relative merits of the large aperture and small aperture approaches to a "modern" Michelson interferometer have been outlined previously[18], and, as neither is a completely proven technique, it is not clear which is best suited for high resolution stellar studies. A larger aperture amplitude interferometer is likely to have the edge in sensitivity, but the work of Twiss and Tango with the Monteporzio small aperture amplitude interferometer[14] suggests that V(limit) = +8 or +9 could be achieved using their approach, and this would be adequate for a wide range of stellar programmes[10]. In both cases there are a number of questions, particularly concerning the accuracy that can be achieved in measuring fringe visibility through the atmosphere, which need answering. While Labeyrie is pursuing the large aperture approach[12], the astronomers at the University of Sydney believe that the small aperture approach is more likely to give the desired accuracy for stellar work.

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4.1 A Prototype Modern Michelson Stellar Interferometer

The Chatterton Astronomy Department of the University of Sydney is currently investigating the feasibility of a "modern" Michelson interferometer by building a small prototype instrument. The aim is to establish, by observations of both unresolved stars and stars measured with the Narrabri Intensity Interferometer, whether fringe visibility can be measured with an accuracy better than ± 2% over a range of atmospheric conditions and instrumental parameters.

The prototype instrument represents a logical step in the work carried out by Twiss and Tango with the Monteporzio two-metre amplitude interferometer[14]. These authors have described the principles and theory of a small aperture amplitude interferometer[19,20] and they apply directly to the prototype instrument. The design considerations and a description of the layout of the prototype instrument have been published[21,22].

The prototype interferometer will have a fixed 11-metre North-South baseline and siteworks for the instrument, including concrete piers anchored securely in rock to support the various components, are nearing completion in the grounds of Australia's National Measurement Laboratory near Sydney. While it is dangerous to make predictions it is planned to align the interferometer and carry out a programme of test observations in 1982 which should prove the viability of the technique and enable the instrumental parameters (apertures, optical bandwidths, seeing and path-length compensation servo bandwidths, etc.) to be optimised. The sensitivity limit which is expected to be V(limit) ≥ +8 will also be established in this programme.

4.2 The Future

The prototype interferometer is intended to be the stepping stone to a major long baseline instrument and the component parts have been designed with this in mind. Providing there are no unforeseen problems, and that the test programme with the prototype is completed as planned, it is intended to proceed quickly to the next stage. A search for a suitable site will be undertaken in 1982 with the aim of installing the prototype as the heart of the major instrument in 1984. With this approach, it should be possible to commence an astronomical observing programme within about a year of establishing the site. The proposal is to commence with East-West baselines and to increase the maximum baseline by geometrical progression to $\sim$ 1 km over a period of about 5 years. One of the criteria in selecting a site will be that it is large enough for the installation of North-South baselines, as suggested in Section 2, at a later stage.

5. SUMMARY

Long baseline interferometery has the potential to make significant contributions to the study of binary stars as has been discussed by McAlister[4]. How much of the potential will be realised depends on the development of an interferometer capable of making accurate measurements of $V^2(d)$ through the atmosphere and with long baselines.

Groups in the U.S.A.[15,16] and France[12] are tackling the problems of building a long baseline interferometer as well as the Sydney group. Only time will tell which approach is best for binary star studies. The prototype interferometer under construction in Sydney is nearing completion but, realistically, it will be at least

1984 before binary star studies could be undertaken. In the long term the Sydney programme aims to build a stellar interferometer with baselines to $\gtrsim$ 1 km and with V(limit) $\gtrsim$ + 6.5 for binary stars. Examination of a catalogue of spectroscopic binary systems[23] reveals that there are more than 50 *known* double-lined systems suitable for study with such an instrument.

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