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SPECKLE INTERFEROMETRY IN ASTRONOMY

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ABSTRACT

Speckle interferometry has become an established technique for the measurement of high angular resolution information in astronomy. Although its practical usefulness at the moment is restricted to the observation of binary stars, the potential applications for developments of the technique are very broad.

In this paper the basic principles of speckle interferometry are reviewed and some topics of current interest are discussed. An extensive bibliography on all aspects of stellar interferometry is given at the end of the paper.

RESUMEN

La interferometría de manchas se ha convertido en una técnica aceptada comúnmente para mediciones astronómicas que requieran una gran resolución angular. Si bien su utilidad práctica se limita por ahora a la observación de estrellas binarias, el futuro desarrollo de esta técnica permite prever un amplio campo de aplicación.

En este artículo se revisan los principios básicos de la interferometría de manchas, y se discuten algunos tópicos de interés actual. Al final del artículo se presenta una extensa bibliografía sobre todos los aspectos de la interferometría estelar.

I. INTRODUCTION

Even at the very best sites of Earth-based telescopes, the angular resolution is limited by atmospheric turbulence, or "seeing", and not by the theoretical diffraction limit of the telescope. The diffraction limited angular resolution, as measured by the classical Rayleigh criterion, is given by

$$\alpha = \frac{1.22\,\lambda}{D} \quad . \qquad (1)$$

Thus for a wavelength of 400 nm, for example, a 4-m telescope should have an angular resolution of approximately 0.025 arc seconds, whereas in practice the seeing limits the resolution to one or two arc seconds, a loss in resolution of 40-80 times.

In 1868, Fizeau suggested a new method of overcoming the deleterious effect of the seeing using a double-slit interferometer and Stèphan (1873, 1874) attempted to apply this method to the measurement of stellar diameters using the 80-cm refracting telescope at Marseille. The distance between the slits was 65 cm and this small baseline explains why Stèphan was unable to resolve even the largest stars.

A.A. Michelson (1890) re-invented this technique twenty years later and used it successfully to measure the diameters of Jupiter's satellites (Michelson, 1891). Another thirty years elapsed before the first stellar measurements –in 1920, Michelson and Pease found the angular diameter of Betelgeuse (α Orionis), the first "direct" measurement of the size of a star (apart, of course, from our own sun). Because of stability requirements, Michelson interferometry is difficult to implement and after the pioneering observations by Anderson, Michelson and Pease it fell into disuse until very recently.

In 1957, R. Hanbury Brown and R.Q. Twiss invented a new form of interferometer –the intensity interferometer– for which the stability requirements were greatly relaxed. An interferometer with a baseline of 188 m was built at Narrabri, Australia and used to measure the angular diameters of 32 stars (mainly A and B types) between 1964 and 1972; the limiting magnitude was $m_v = 2.5$. Using the

latest technology, it is estimated that an interferometer with a baseline of 2 km and a limiting magnitude of 7.3 could be constructed at reasonable cost.

The recently renewed interest in stellar interferometry originates from the method of speckle interferometry invented by A. Labeyrie in 1970. In its original form, the resolution is limited to that imposed by the diffraction limit of a single large telescope (i.e. that given by Eq. [1]), although it has been extended to multiple telescope operation. The main advantages of speckle interferometry are that it is relatively easy to carry out in practice and it can also be used to observe fairly faint objects, perhaps as faint as $m_v = 18$.

The basic theory of speckle interferometry is reviewed in the following section. Section III describes the instrumentation used for speckle interferometry; some results and applications in astronomy are given in section IV. The final section is devoted to particular aspects of the technique that are of current interest; these are signal-to-noise ratio, phase recovery and long baseline operation. A bibliography containing over 250 references on all types of stellar interferometry is given at the end of the paper.

II. THEORY OF SPECKLE INTERFEROMETRY

Figure 1 shows a series of three short exposure ($\approx 10^{-2}$ s), narrowband ($\Delta\lambda \approx 20$ nm) photographs of the image of an unresolvable star (γ Orionis) taken at the focus of the 4-m Anglo-Australian telescope*. The random image structure is called "speckle" and its presence is due to the point-like nature of the source of light and the atmospheric seeing. The statistics of this pattern are similar to those of a laser-produced speckle which is almost invariably observed in any experiment involving lasers. In particular, it can be shown that the minimun speckle "size" is of the same order of magnitude as the diffraction limited Airy disc, even if the telescope has aberrations (Dainty, 1973).

Mathematically, each of the image intensities shown in Figure 1 can be represented by a function $P(x, y)$, called the instantaneous point spread function. For any isoplanatic incoherent optical system, the imagen intensity $I(x, y)$ is related to that of the object $O(x, y)$ by a convolution relationship:

$$I(x', y') = \iint_{-\infty}^{\infty} O(x', y') \;\; P(x - x', y - y')\, dx'\, dy' = O(x, y) \circledast P(x,y). \tag{2}$$

* The photographs shown in Figures 1, 2, 6 and 8 were kindly supplied by Dr. B.L. Morgan and colleagues of the Astronomy Section, Blackett Laboratory, Imperial College, London.

Fig. 1. Short exposure, narrowband photographs of the image of an unresolvable star (γ Orionis). Taken on the 4m Anglo-Australian telescope. The minimum speckle size of the same order as the Airy disc of the telescope aperture.

Fig. 2. Short exposure, narrowband photographs of the image of a resolved star, Betelgeuse, taken on the 4m Anglo-Australian telescope. The speckles are blurred in comparison with those of Figure 1, indicating the extended nature of the star.

The image of a small extended object is therefore a "blurred" version of the image of a point object, the blurring function being $O(x, y)$. Figure 2, which shows short exposure images of the resolvable giant star Betelgeuse, illustrates this result; the individual speckles are now blurred, in comparison with those in Figure 1, indicating that an extended object is being imaged.

In order to extract object information from data such as that shown in Figures 1 and 2, some kind of statistical analysis of many short exposure photographs is necessary. There are two equivalent methods of analysis – the autocorrelation method and the power spectrum method.

In the autocorrelation method, an estimate of the ensemble average spatial autocorrelation of the image intensity is found:

$$C(\Delta x, \Delta y) = \iint_{-\infty}^{\infty} I(x, y) \quad I(x + \Delta x, y + \Delta y)\, dxdy$$
$$= I(x, y) \star I(x, y)$$
$$= \left\{O(x, y) \circledast O(x, y)\right\} \star \left\{P(x, y) \circledast P(x, y)\right\} \quad (3)$$

In the power (or, more correctly, energy) spectrum method, we find the quantity

$$W(u, v) = \langle |\tilde{I}(u, v)|^2 \rangle$$
$$= |\tilde{O}(u, v)|^2 \cdot \langle |\tilde{P}(u, v)|^2 \rangle , \quad (4)$$

where the tilde denotes the Fourier transform, for example,

$$\tilde{I}(u, v) = \iint_{-\infty}^{\infty} I(x, y) \exp\left[-2\pi i(ux + vy)\right]\, dxdy .$$

By invoking the autocorrelation theorem of Fourier transforms, it is straightforward to show that $C(\Delta x, \Delta y)$ and $W(u, v)$ are Fourier transform pairs, so that knowledge of either function is equivalent to that of the other. We shall discuss implementation of both methods in section 3.

Eq. (4) states that image and object power spectra are linearly related, the object power spectrum being weighted by the function $\langle |\tilde{P}(u, v)|^2 \rangle$. This function is usually called the speckle transfer function and it indicates the extent to which the different spatial frequency components of the object power spectrum are attenuated by the atmosphere-telescope combination. It is given by (Korff, 1973; Dainty and Greenaway, 1979)

$$\langle |\tilde{P}(u, v)|^2 \rangle \approx |\langle \tilde{P}(u, v) \rangle|^2 + 0.435 \left(\frac{r_0}{D}\right)^2 T_D(u, v) . \quad (5)$$

Here, D is the telescope diameter, r_o is Fried's coherence length (typically 5 – 20 cm in good seeing) and $T_D(u, v)$ is the *diffraction limited* transfer function of the telescope. Eq. (5) is valid only for $D \gg r_o$, but in that limit it appears to be independent of the detailed statistical model used for the atmospheric seeing. It shows that there is a (small) component in the speckle transfer function that is proportional to the diffraction limited transfer function of the telescope and therefore it follows that object structure down to this limit can be measured using the technique of speckle interferometry.

It is clear from Eqs. (4) and (5) that the technique of speckle interferometry as described above does not give the object intensity distribution; furthermore, given the autocorrelation function or power spectrum of the object it is not possible, in general, to reconstruct a picture of the object. This so-called "phase problem" –the phase of the object transform is missing– will be discussed further in section V.

III. INSTRUMENTATION AND TECHNIQUES

At the present time, there are two generations of instrumentation for speckle interferometry. The first generation systems are based on Labeyrie's original equipment (Gezari *et al.*, 1971) which used photographic film recording and optical power spectrum analysis. Several film systems have been built (for example, Beddoes *et al.*, 1976; Breckinridge *et al.*, 1979) and nearly all of the significant astronomical results have been obtained using these systems. Second generation systems, again inspired by the Labeyrie's group (Blazit *et al.*, 1975), use a photon counting detector and some degree of on-line data reduction based on the autocorrelation method.

Figure 3 shows the speckle camera system of Beddoes *et al.* (1976). The instrument is mounted at the Cassegrain focus and a combination of a microscope objective and another lens forms a magnified image of the star (typically 10-20X) on the photocathode of an image intensifier. The exposure time is controlled by a rotating sector at the Cassegrain focus, the bandwidth by an interference filter and a pair of prisms are used to compensate for atmospheric dispersion. This particular image intensifier is a four-stage electromagnetically focussed cascade tube (EM1 type 9412) with a maximum gain of order 2×10^6. The images are recorded on 16 mm reversal cine film that is commercially developed; about 1000 frames are recorded in a typical observation.

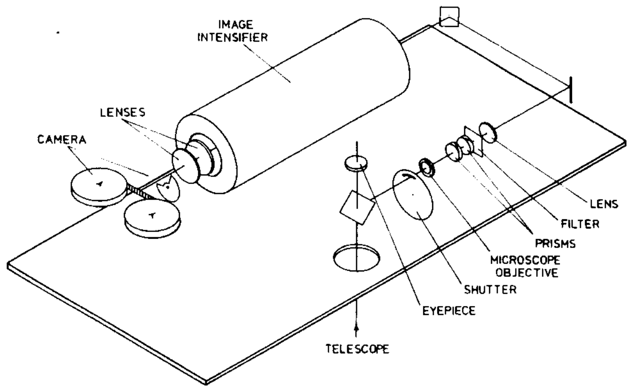

Fig. 3. A first generation speckle camera system.

Images recorded on film are particularly suitable for the power spectrum method of analysis, using a coherent optical system such as that shown in Figure 4. It can be shown that the intensity distribution in the Fraunhofer (far-field) diffraction pattern is the squared-modulus of the Fourier transform of the amplitude transmittance of the film. If we assume that the amplitude transmittance is directly proportional to the original image intensity, then this optical system automatically performs the mathematical operation described by Eq. (4), if an average intensity (from many frames) is recorded in the diffraction plane.

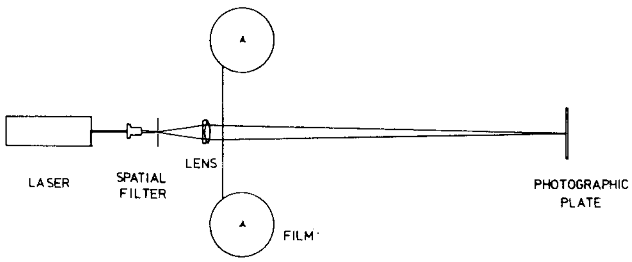

Fig. 4. A simple coherent optical processor for power spectrum analysis.

The advantage of the film method is that it is simple and inexpensive. Unfortunately, it has a few drawbacks: film non-linearity, various unwanted noise sources and a practical limit on the maximum number of frames that can be analyzed. The ultimate sensitivity limits in speckle interferometry are set by photon noise, but it is difficult to achieve this by using film to record the output of the image intensifier.

Second generation speckle interferometers differ from the first generation instruments only in the detector and method of data processing. By using either a charge coupled device (CCD) or television tube after the intensifier, a photon counting detector can be made. Since speckle images of most real objects contain only a few detected photons, it is necessary to store only the coordinates of detected photons rather than a very large array consisting of the whole image. It is possible to process this data digitally in real time by the autocorrelation method (Blazit *et al.*, 1975). The block diagram of one such processor is shown in Figure 5. In this particular device, the cross-correlation of frames separated by up to eleven exposures is found at the same time as the autocorrelation of individual frames. The autocorrelation is found by finding the vector difference between all possible pairs of photon coordinates (within a window) and incrementing by one an address in memory which is given by the vector difference. The process is repeated for many frames and can be shown to give a map of the autocorrelation function of the image intensity. With typical integrated circuits of modest speed, it is possible to autocorrelate frames with up to several hundred detected photons at a rate of fifty per second.

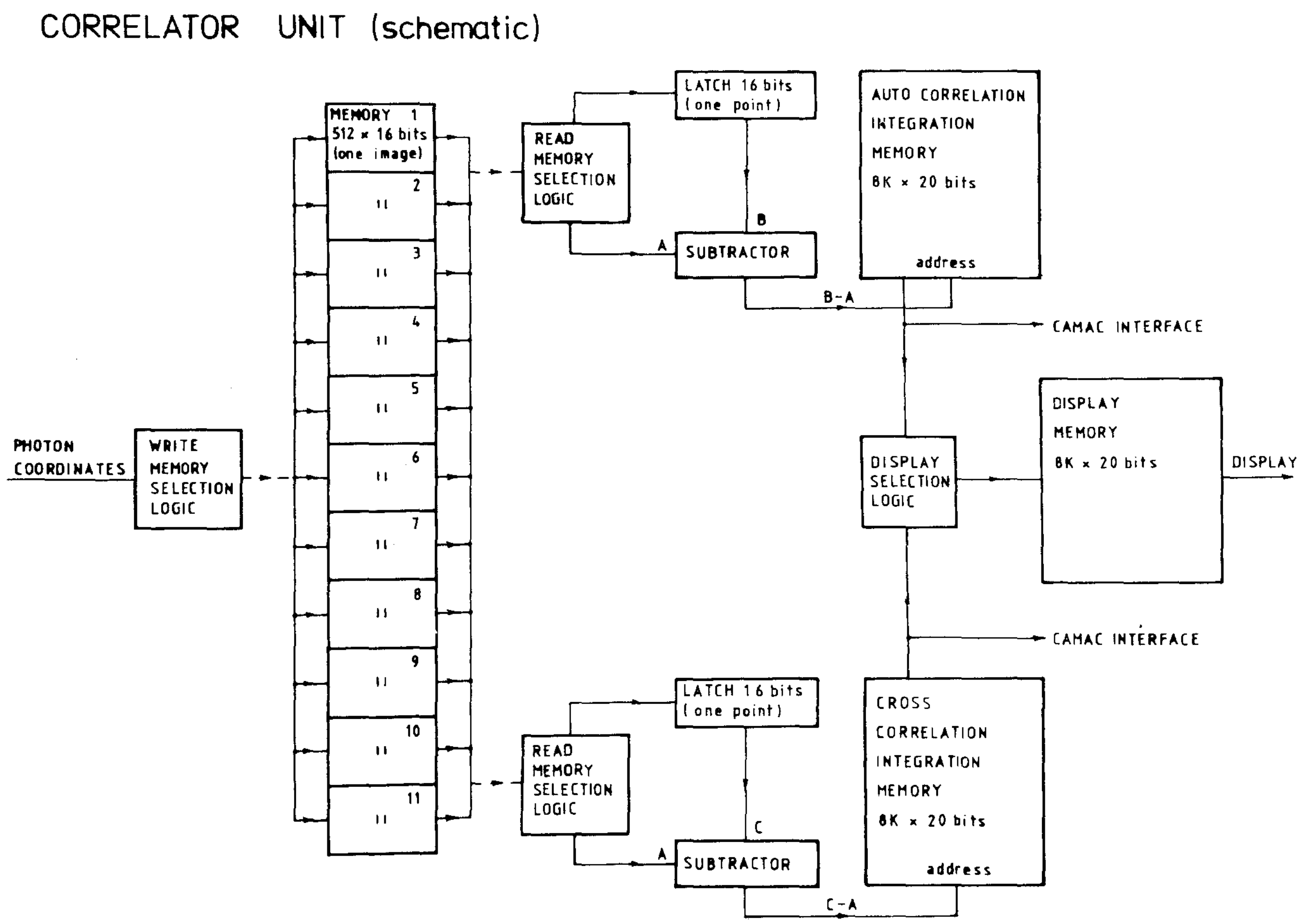

Fig. 5. Schematic diagram of a correlator used for on-line analysis of photon counting data in speckle interferometry.

IV. RESULTS AND APPLICATION IN ASTRONOMY

The most fruitful application of speckle interferometry in astronomy has been in the study of binary stars, mainly by McAlister (see bibliography). To date, at least 40 new systems have been directly resolved for the first time and highly accurate measurements made on several hundred others. The results of most importance given by binary star speckle interferometry are the individual stellar masses and distance to the system, which can be found for double-lined spectroscopic binaries independently of any further assumptions; this provides very reliable data for the empirical mass-luminosity relation in a region that bridges purely visual and purely spectroscopic data. With single-lined systems, the individual masses can be found if the parallax is known; however, it is not usually known, and in that case one has to rely on the magnitude difference to enable individual masses to be found.

Speckle power spectra for some binary stars are shown in Figure 6; the fringe spacing and orientation give the separation and position angle of the binary. Such measurements, if they are made on a systematic basis, enable the orbit of the binary to be found. An example of such an orbit for the double-lined, 331 day spectroscopic binary 12 Persei is shown in Figure 7 (McAlister, 1978). These observations, in addition to the spectroscopic data, enabled all the parameters of the orbit to be found and gave individual masses of 1.25 ± 0.20 and 1.08 ± 0.17 solar masses, and a parallax of $0.''046 \pm 0.''002$.

Apart from mass and distance determination, binary star interferometry may be a possible technique for the detection of large planets, if such objects exist in stable configurations with binary stars. It is the very high accuracy of speckle interferometry that could enable perturbations on the binary orbit to be possibly detected.

The other main application of speckle inferometry is to the determination of angular diameters of objects. Using a single telescope, measurements have been reported on a diverse range of objects; the asteroids Pallas (Worden and Stein, 1979) and Vesta (Worden *et al.*, 1977), Pluto (Arnold *et al.*, 1979), many giant stars, and some peculiar stars (for example, Nova Cygni 1975 in Hα emission by Blazit *et al.*, 1977). The development of long baseline speckle interferometry has enabled much higher angular resolutions to be attained, an example being the resolution of the diameters of the individual components of the binary star Capella.

V. POTENTIAL OF SPECKLE INTERFEROMETRY

One of the important advantages of speckle interferometry is the ability to make measurements on relatively faint objects. In practice, speckle patterns such as the ones shown in Figure 1 and 2 are only observed for the very brightest stars. Fainter stars, when recorded with a quantum-limited detector, give patterns more like the one shown in Figure 8, in which individual photo-electron events can be clearly seen. In the visible region of the espectrum, it is this photon noise in the signal that dominates over other sources of noise.

The limiting magnitude depends upon the type of object that is being observed and the maximum error of measurement that can be tolerated; this topic is reviewed in detail in Dainty and Greenaway (1978). For binary stars, a limiting magnitude of $m_v = 18$ in a one hour observing time is not unrealistic. Although this has not yet been achieved, measurements on 15th magnitude objects have been reported (Arnold *et al.*, 1979); for these objects, there are an average of only three or four detected photons per frame and 10^5 frames are needed to achieve an adequate signal-to-noise ratio.

For very faint objects, it is necessary to extract every bit of information from the available signal and some kind of space-time analysis, in which both the space and time coordinates of detected photons are used in the data processing is called for. At a simpler level, it is necessary to optimize the exposure time of the individual exposures. That is, given a certain total observing time, should we take more frames with a shorter exposure time or fewer frames each with a larger exposure? Intuitively, the exposure time should be of the same order of magnitude as the correlation time of the speckles in the image. In fact, as Figure 9 shows, the highest signal-to-noise ratio is obtained for exposure time approximately twice as long as the speckle correlation time, at least for photon limited signals.

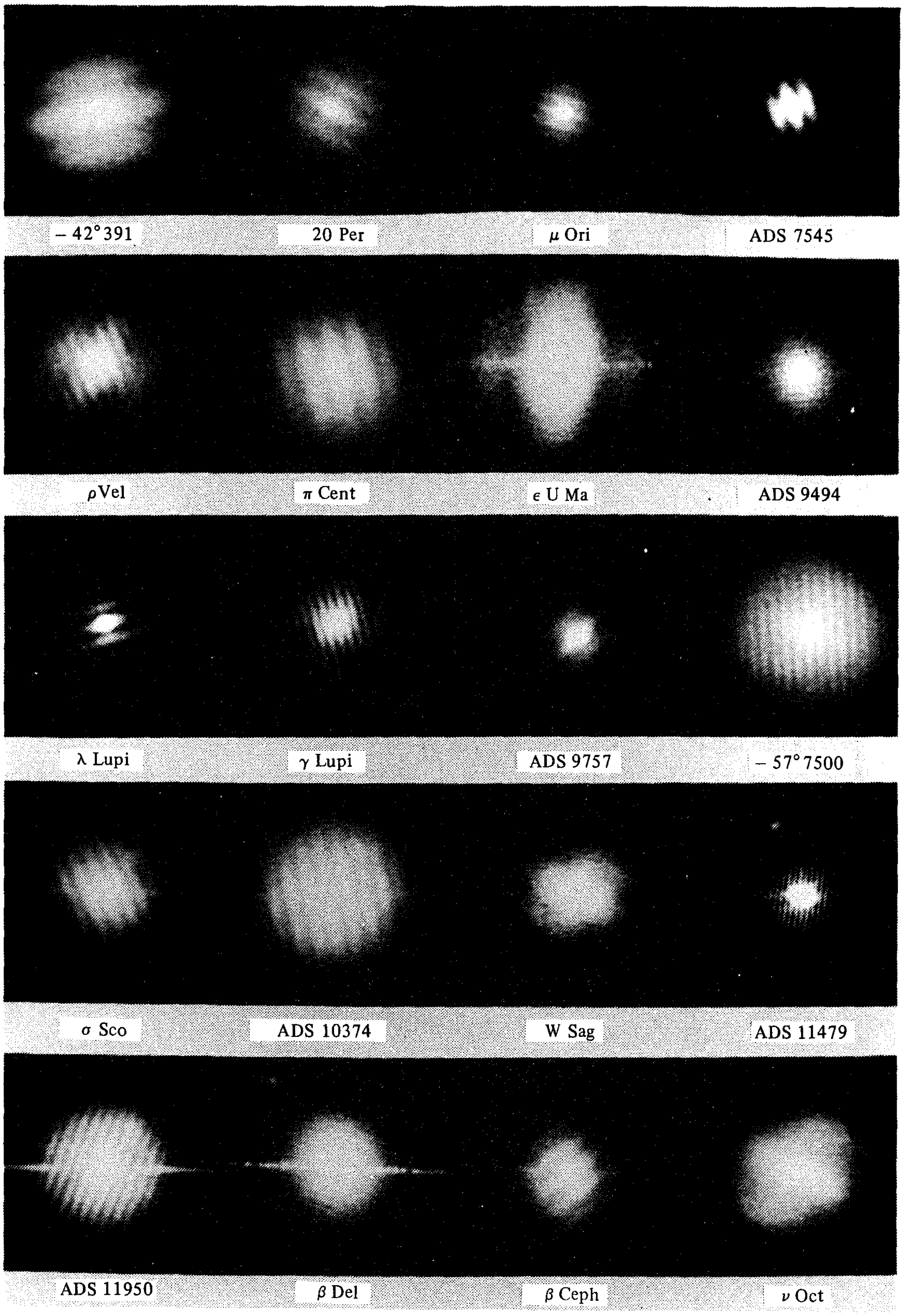

Fig. 6. Some power spectra of resolved binary stars (after Morgan *et al.*, 1978).

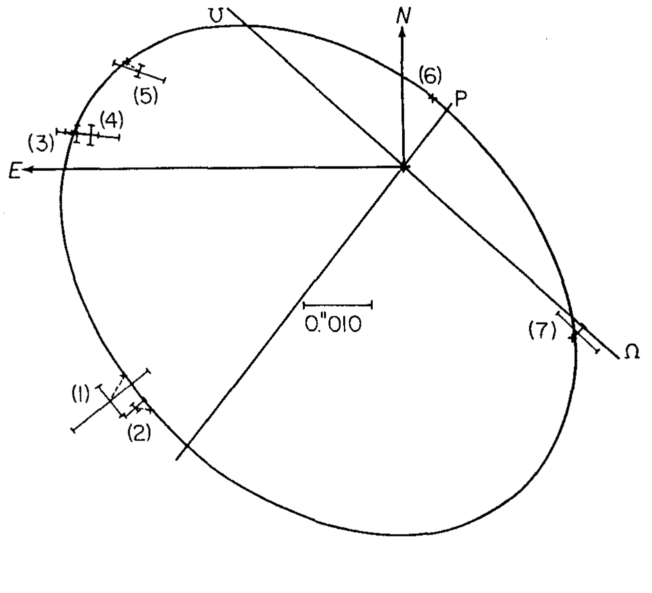

Fig. 7. Six speckle observations and their error bars are shown on the deduced visual orbit of 12 Persei. The + symbols mark the expected positions at the corresponding epochs (McAlister, 1978).

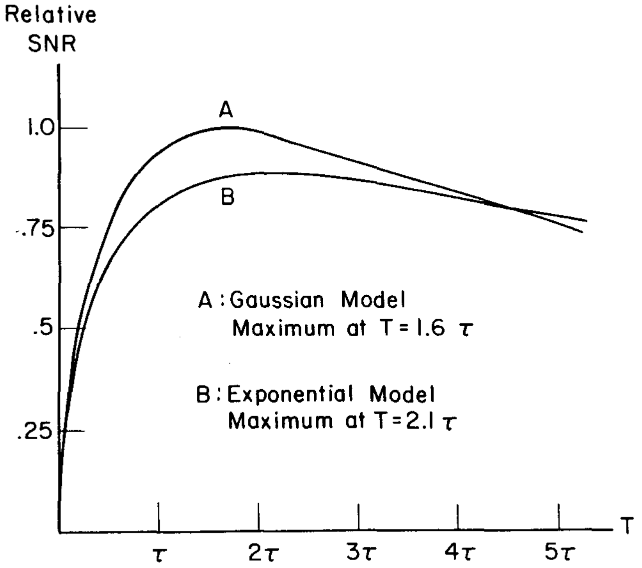

Fig. 9. Relative signal-to-noise ratio (SNR) as a function of exposure time for two different models of the speckle (time) correlation function.

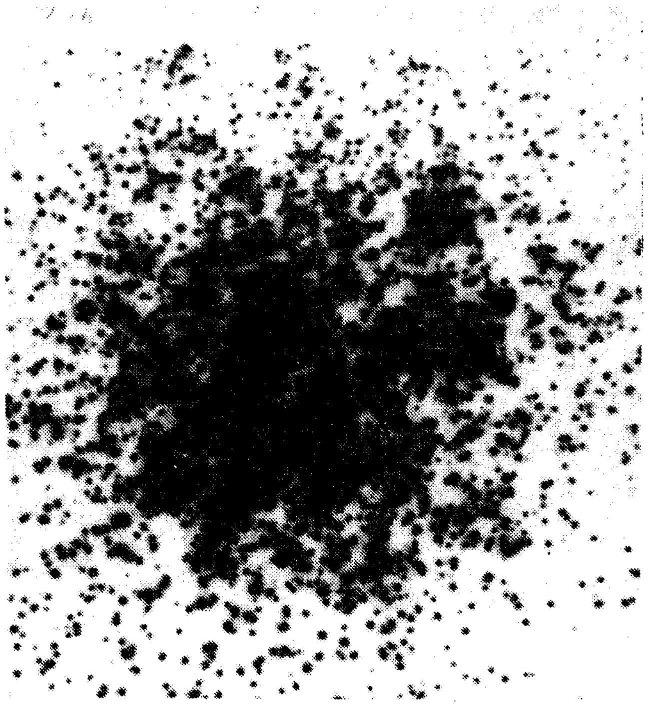

Fig. 8. A short exposure, narrowband photograph of an unresolved faint star, showing individual photo-electron events clumped into speckles.

The "phase problem" in speckle interferometry is concerned with finding the phase of the Fourier transform of object intensity or, equivalently, finding the object intensity itself. Given merely the object autocorrelation or its power spectrum it is not in principle possible to construct a unique solution for the phase. In one dimension, there can be a large number of possible solutions, all consistent with the modulus data. In two dimensions, it appears from the computer-based studies of Fienup (1978, 1979) that the ambiguity is less than in one dimension, at least for "realistic" objects. This particular aspect of the phase problem awaits further theoretical advances.

Additional information obtained from the data in speckle interferometry may help to solve the phase problem; several different techniques have been proposed with varying degrees of success (Knox and Thompson, 1974; Lohmann and Weigelt, 1977; Aitken and Desaulniers, 1979; Mertz, 1979). One technique, that of Lynds *et al.* (1976) has been applied to the giant star Betelgeuse. Their results are shown in Figure 10 and claim to show possible temperature fluctuations over the surface of the star.

Speckle interferometry is being extended to operate at long baselines using two separated, large telescopes (Blazit *et al.*, 1977). A baseline of 100 m would enable angular diameters as small as 5×10^{-4} arc seconds to be measured and limiting magnitudes as faint as $m_v = 10$ appear possible. Combined with some tech-

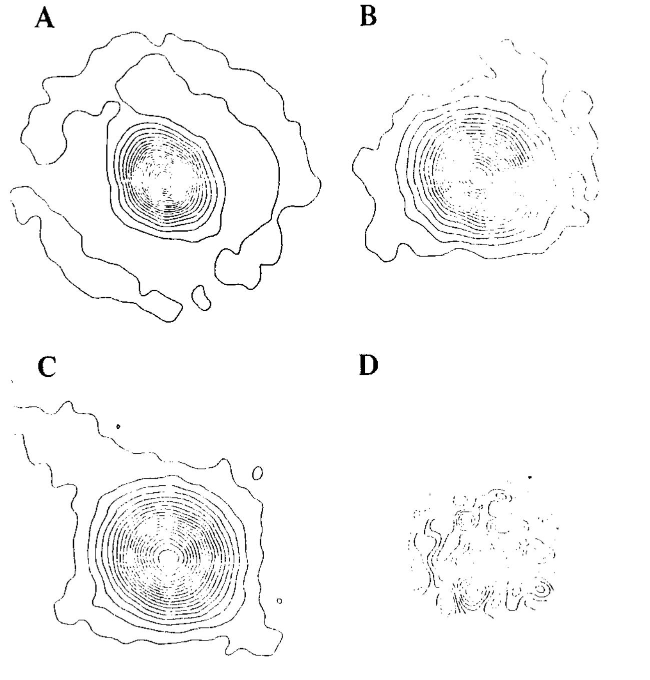

Fig. 10. Diffraction-limited images of Betelgeuse computed from short exposure photographs by Lynds *et al.* (1976). A: unresolved star, B: Betelgeuse in the continuum, C: Betelgeuse in the TiO band and D: the difference between B and C showing a possible temperature fluctuation over the star.

nique of phase retrieval, long baseline speckle interferometry could make a substantial contribution to optical astronomy, somewhat akin to that of interferometers in radio-astronomy.

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DISCUSSION

Ridgway: What constitutes a good site for a speckle work, and, at a given site, are there

clear-cut considerations for adjusting your observing parameters to suit the prevailing conditions?

Dainty: I'll answer your second question first. No, there are no clear-cut decisions. Decisions are based upon experience. And the particular site parameter that turns out to be very important indeed is the time-scale of the turbulence. Now, of course, this is not just the image diameter, the conventional seeing, although it does tend to happen that when you have a poor seeing in the sense of a wide conventional image diameter, you would also probably have a faster time-scale, although not always. So, I would regard the time-scale as the single most important aspect. Now, this is because when you are photon limited, you want as long an exposure as possible, consistent with freezing the seeing (assuming you use a single exposure technique as I have described here). It is better to take a few pictures with lots of photons per picture (after all, you are trying to occupy all those speckles), than to take many pictures with fewer photons; all this can be shown quite rigorously. I should also say that the proper analysis should be a continuous space-time analysis, and we are doing some work on this at the moment. One can envisage future detectors that will give you *xy* and time coordinates of photons, instead of seeing snapshots as we have now. But in my feeling, this will give you an increase of only one or two magnitudes in the limiting magnitude.

R. Lynds: Those of you who observe have probably encountered nights of terrible seeing (you know what I mean) and on those nights the frequencies were very high. From your speckle work, would you say that this is a correct statement?

Ridway: Yes, it is. In fact, the way we determine exposure times is, you look at the images highly magnified, and if you can see beautiful speckles, you know you can give a long exposure time because of the time constant of the eye. When we really can't see much, we know it is not because they are not there, but because the time constant of the eye is blurring them out. But there must be better ways to get exposure times.

Johnson: Oh, a long time ago, I remember arriving at the general conclusion that there is a strong correlation between frequencies and seeing; in fact, the better the seeing the lower the frequencies involved.

Ridgway: Yes, I think that is the general rule. They don't always go hand in hand, though. We certainly have counter-examples on particular nights, on particular locations.

Johnson: What we had was that when the seeing was bad the frequencies were always fast, but if the seeing was good the frequencies might not be slow.

M. Burbidge: You said that with the Isaac Newton telescope you could go as faint as the 18th magnitude with double stars. How faint do you think you could go with extended objects? I am thinking of the radio sources that the VLBI people work on.

Dainty: Well, first of all, I must have given the wrong impression. To arrive at a limiting magnitude of 18, I had in mind a 4-meter telescope at a good site. Although it is not too telescope-tied, it depends on the diameter, and certainly on the transparency of the atmosphere. Now to answer your question: you lose very heavily when you try to go to an extended object. You lose on signal-to-noise ratio in the rms sense, you lose in inverse proportion to the number of resolution elements over the object. So, if you have ten Airy disks (that's just a factor of 3 in diameter), then you would lower the signal-to-noise by a factor of ten. So, this is a rather severe effect and it gets obviously worse as you go to more and more extended objects.

Poveda: In the case of double stars, what is the minimum separation you can resolve relative to the Airy disk?

Dainty: It *is* the Airy disk, and I showed a particular example there which goes right down to the area disk of that particular telescope. In fact, McAlister has done a lot of very excellent work with the 84-inch telescope. In this sort of program, it is important to maintain continuity over a period of many years and to get a reasonable amount of time. We do observe anything from one hundred to two hundred objects per night; you go very quickly and, in fact, quite a lot of the work McAlister has done and we have done has used not the largest telescopes in the world by any means! Of course, for looking at angular diameters, you do need the largest telescope possible; even if you are looking at 5th or 4th magnitude, you really need the diameter for resolution.

Poveda: And then I have the further question of whether multiple stars could really be resolved without confusion. How do you handle this?

Dainty: Well, it has been tried. It is a bit like some of the work in radioastronomy. It is like solving a jigsaw puzzle, It is OK with three stars, although you have a certain ambiguity in the solution. With four stars you have more ambiguity, more possible solutions. And, really, you have to think about solving the so-called phase-problem before you can get reliable images of multiple stars.

Bok: Do you have plans to survey stars with unknown spectra?

Dainty: At present, we are looking at variable stars part of the time, and at known spectroscopic binaries, because then we have enough information to get accurate masses of both components, and also their distance. I am not sure about the other programs, but we have certainly discovered several new binaries.