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SPECKLE INTERFEROMETRY: DIFFRACTION-LIMITED MEASUREMENTS OF NINE STARS WITH THE 200-INCH TELESCOPE*

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ABSTRACT

A new method has enabled us to repeat most of the classical Michelson-Pease measurements of stellar diameters. Stellar images are photographed "coherently" with a special camera. They contain a fine structure from which diffraction-limited information is extracted by optical processing. Nine of the stars observed were resolved, showing angular dimensions as small as 0″.016. Limb darkening is evidenced in α Ori, and a faint companion is found for β Cep.

I. INTRODUCTION

Stellar dimensions have previously been measured by using classical double-aperture interferometry (Michelson and Pease 1921; Anderson 1920), lunar occultation (Evans 1955), and intensity interferometry (Hanbury Brown and Twiss 1958). Each of these methods has been successfully applied to a particular class of objects. An excellent review was presented by Hanbury Brown (1968). We report here on our observations using "speckle interferometry," a different approach which utilizes the full aperture of a single large telescope. High-resolution information is extracted, by means of Fourier analysis, from the cellular sub–arc-second "speckle" detail observable in stellar images. The speckle pattern is an interference effect in the image caused by random phase and amplitude perturbations impressed upon the incident wave front by atmospheric turbulence and telescope aberrations. The theory of the method has already been presented by one of us (Labeyrie 1970).

The practical resolution limit of the method is presently 0″.010 for stellar objects as faint as $m_v = +9$. Measurements are restricted to such centrosymmetric stellar features as diameters, binary structure, oblateness, and limb darkening. With instrumentation used at the 200-inch (508 cm) telescope, we have measured stellar diameters as small as 0″.016. The dimensions of many of the objects we observed agree well with results obtained by using different methods; however, several objects showed unexpected stellar features.

II. INSTRUMENTATION AND DATA REDUCTION

An image-tube camera system was installed at the east-arm Cassegrain focus of the 200-inch telescope to photograph the stellar images. The recording requirements are: (1) short exposure times, between 0.125 and 0.001 seconds; (2) restricted spectral bandpass of 250 Å to make visible a large number of high-contrast speckles; (3) long equivalent focal length of f = 35,000 inches (889 m) producing a film scale of 2″.5 cm^{-1}, and (4) compensation for differential atmospheric refraction. The bandpass restriction and dispersion correction are made with a field grating in the plane of the magnified intermediate image by employing a design comparable to that of the Courtès multiband camera (Courtès 1962). One or more narrow-bandpass images are formed on the first stage input of two optically coupled ITT/4708 image tubes, equipped with a motorized

* This article is based on observations made by the authors as guest investigators at the Hale Observatories.

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film transport and shutter. A typical observation consists of a sequence of 250 exposures on Kodak Tri-X film, half of the object of interest and half of a nearby reference star using identical exposure times and focus settings. Reference stars are chosen to be unresolvable and to have nearly the same zenith distance and apparent magnitude as the object of interest.

In a second step, the two-dimensional intensity Fourier transform of each of the developed negative images is produced with a laser-illuminated optical system employing the classical aperture/image relationship of coherent optics. 125 Fourier transforms are co-added to make a composite transform with improved signal-to-noise ratio by successive multiple exposures on a single photographic plate. The bright central peak of the transform is suppressed with a small opaque mask to avoid halation effects in the emulsion, and apodization is employed in the negative plane to reduce edge effects. Kodak 649F plates or Polaroid PN film are used for co-adding the transforms, and a step wedge exposure is made for sensitometric calibration.

The intensity profile of this composite transform is now divided by the profile of a similarly produced reference-star transform (Labeyrie 1970). The result is the two-dimensional equivalent, in squared modulus form, of the visibility curve obtained by Michelson and Pease. Its detailed form is determined by the star's diameter, limb darkening, and oblateness, or by its binary parameters. The central part of the visibility function (perturbed by the central peak) and the outer part (most affected by noise) are not usable.

To determine the stellar diameter, a fit is made in the intermediate part of the profile to the theoretical profile of a uniform disk object. If the half-power width w is used as a fitting parameter, the diameter α of a uniform stellar disk is given by

$$\alpha = 1.02\lambda_0 \mathrm{f}'/w\mathrm{f} , \tag{1}$$

where λ_0 is the laser wavelength and f and f′ are the equivalent focal lengths of the telescope and Fourier-transform apparatus.

The presence of straight, equispaced fringes in the transform indicates binary geometry, and the separation ρ is derived from the fringe spacing s, using the relation

$$\rho = \lambda_0 \mathrm{f}'/s\mathrm{f} . \tag{2}$$

The magnitude difference Δm of a binary is derived from the fringe contrast C, using the relations

$$C = (I_{\max} - I_{\min})/(I_{\max} + I_{\min}) , \quad \Delta m = 2.5 \log \frac{1 + (1 - C^2)^{1/2}}{1 - (1 - C^2)^{1/2}} . \tag{3}$$

III. OBSERVATIONS

Coherent photographs of unresolved stars (fig. 1 [pl. L1]) were found to closely resemble the simulations published with Labeyrie's original article. The statistical properties of the pattern appear to be relatively insensitive to changes in quality of the seeing as long as the distribution of phase and amplitude defects on the wavefront are random. It should be noted, however, that our attempts to record speckle at the Mount Hopkins 60-inch (152 cm) telescope and those of Kent *et al.* (Schneiderman 1972) at the 60-inch telescope of the ARPA Maui Optical Station were sometimes unsuccessful for reasons that are not yet clear. Nevertheless, it appears that the primary effect of seeing is on the overall size of the image. The number of speckles *per arc second* across the image is directly proportional to the diameter of the telescope aperture and inversely proportional to the wavelength of observation. With 2″ seeing there are approximately 1000 speckle grains in a stellar image produced by the 200-inch at 5000 Å with a 250 Å bandpass. From the simultaneous photographs made in blue, green, yellow, and red light, and also from infrared photographs made at 1 μ, the minimum size of

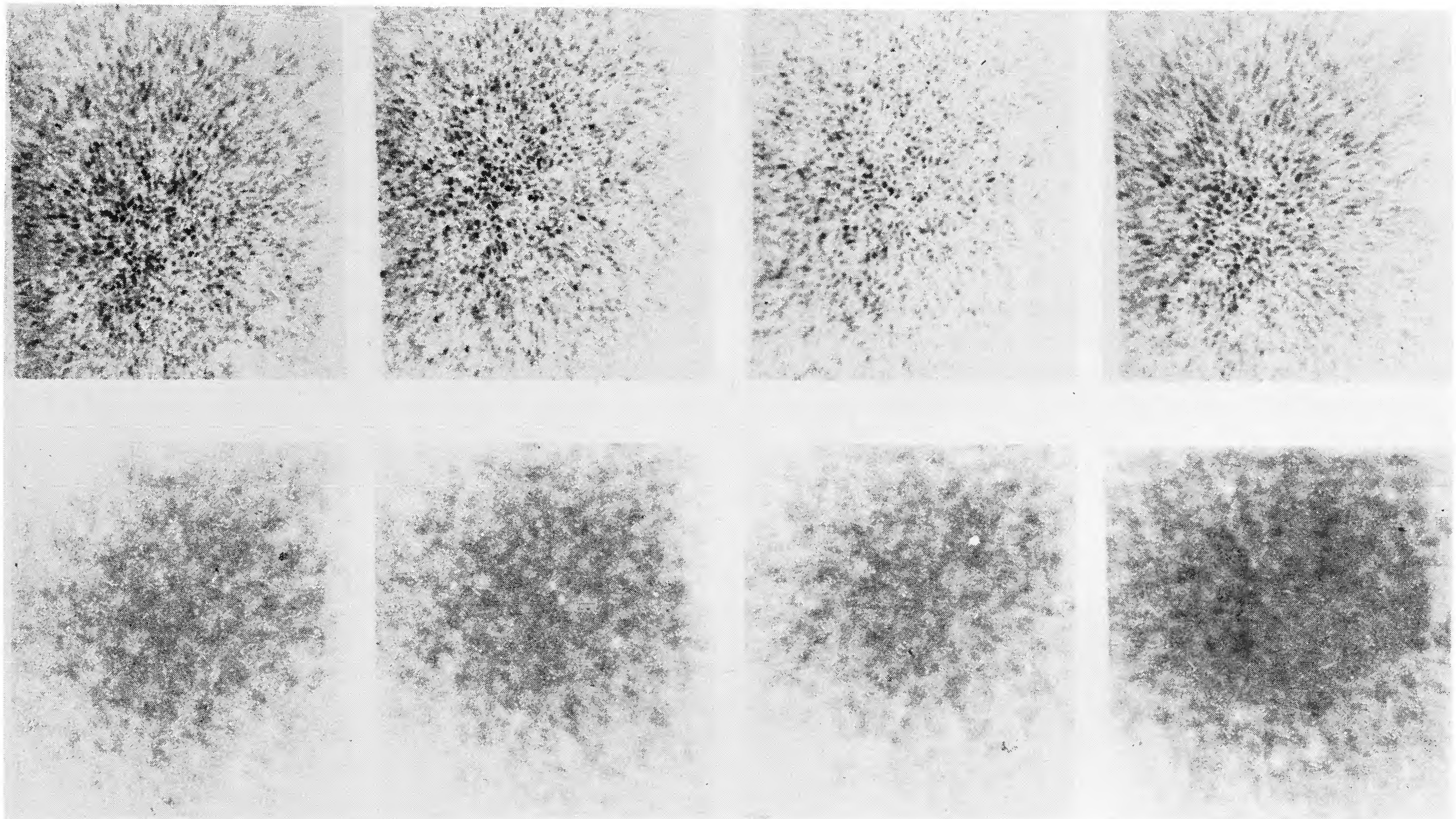

FIG. 1.—Simultaneous images in four colors, for unresolved (α Lyr, *top*) and resolved (α Ori, *bottom*) stars. The colors (and spectral bandwidths) are from left to right: blue (250 Å), green (250 Å), yellow (250 Å), and red (500 Å).

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speckle granules was found to be proportional to wavelength. This confirms the diffraction/interference nature of speckle and rules out ray-optics interpretations of the phenomenon. It also justifies *a posteriori* the use of a narrow spectral bandwidth. In white light only a few speckle granules are visible, as reported by previous observers (Gaviola 1948; Rösch 1958; Texereau 1961; Vaughan 1971). Although the 200-inch primary has not been figured to meet the Rayleigh tolerance, the smaller speckle granules are found, as expected, to have the same size as the ideal Airy spot produced by a diffraction-limited 200-inch aperture.

Observations were made during twilight on 11 dates in 1971 April, June, and October, with seeing from 1″ to 3″. Except for binaries, none of the transforms of resolved stars show departures from symmetry indicating oblateness in excess of the estimated 5 percent error. Figure 1 shows α Ori and α Lyr, the latter a typical reference star; figure 2 (plate L2) shows a number of composite transforms. Some of the objects were readily recognized as resolved from their appearance in the reflex viewfinder of the recording camera. Table 1 shows the principal stellar measurements together with previous determinations by other methods. The diameters are based on the assumption of uniform disk brightness, as given by equation (1). The measurements of α Sco, β Peg, α Her, and α Boo are in good agreement with previous determinations.

Five fringes, indicating separations of approximately 0″.05, were observed in the transforms of α Aur (Capella) (fig. 2) at position angles consistent with those predicted from Merrill's (1922) ephemeris. The fringes show 90 percent contrast, and the brightness difference between the two stars is found from equation (3) to be $\Delta m \leq 1.0$ at 5000 Å. With better calibration of the equivalent focal length and position angles, the prob-

TABLE 1

OBSERVED STELLAR DIMENSIONS AND PREVIOUS MEASUREMENTS

Object	Observed Angular Dimensions: Diameter (″)	Observed Angular Dimensions: Binary Separation (″)	Previous Measurements: Diameter (″)	Previous Measurements: Binary Separation (″)	Previous Measurements: Observer
α Sco	0.042±0.002	...	0.040	...	Pease (1931)
			0.039	...	Evans (1955)
β Peg	0.016±0.002	...	0.021	...	Pease (1931)
α Tau	?*	...	0.020	...	Pease (1931)
α Boo	0.022±0.003	...	0.020	...	Pease (1931)
α Her	0.031±0.003	...	0.030†	...	Pease (1931)
α Aur	...	0.057±0.004	...	0.0507‡ (0.0536)§	Merrill (1922)
β Cep	...	0.255±0.010‖	...	...	
μ Cas	...	#	...	$\lesssim$1.04	Hegyi and Currott (1970) Faulkner (1971)
α Ori	>0.05**	...	0.047	...	Pease (1931)
o Cet	>0.05††	...	0.048	...	Pease (1931)

* Resolved but uncertain.

† Uncertain.

‡ Calculated from ephemeris for JD 2,441,034.0.

§ Merrill's semimajor axis.

‖ Previously unobserved.

No companion brighter than $m_v = 9$.

** From visual estimates; probable limb darkening.

†† From visual estimates.

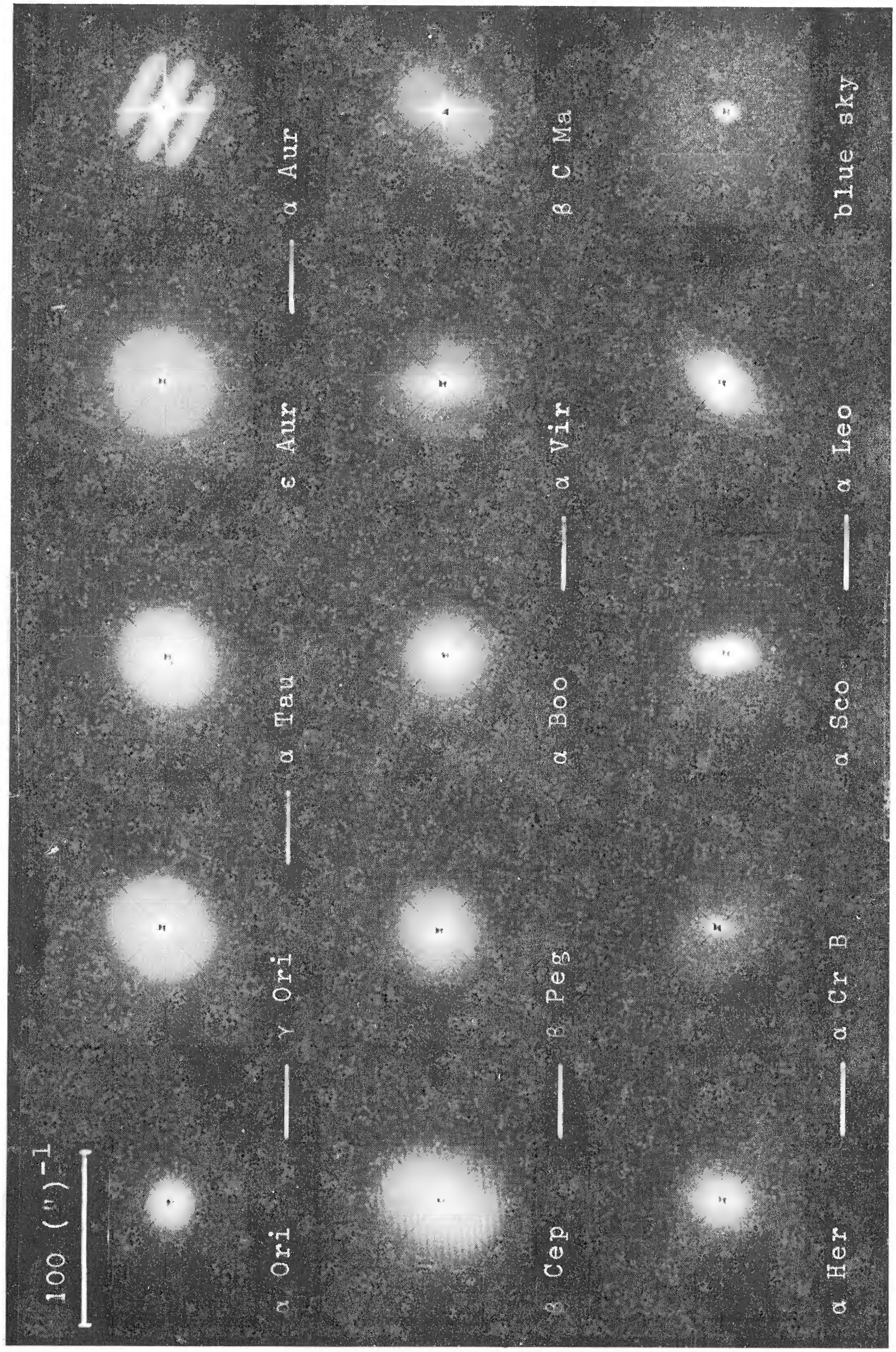

FIG. 2.—Composite Fourier transforms, showing resolution of six stellar disks and two binaries. Object-reference pairs are indicated by a bar. The alteration in the case of β CMa is believed to result from telescope aberrations. The "blue sky" transform shows the effect of pure photon-noise granularity.

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able error in binary measurements should ultimately be on the order of 10^{-4} arc sec in separation and 0°.1 in position angle. Weak effects such as astrometric perturbations on Capella and other spectroscopic binaries should thus become observable.

Twenty-one fringes with 10 percent contrast are visible in the transform of β Cep (fig. 2), the prototype of the β Cephei class of short-period variables characterized by a doubly periodic light curve. It has one previously known companion (ACS 15032) with an angular separation of about 13″. Our observations on JD 2,441,130 show that it has an additional close companion at an angular separation of 0″.255 ± 0″.010. The fringe contrast in the transform yields a brightness difference of $\Delta m = 5$ mag at 5000 Å. Subsequent attempts to observe the companion by conventional visual methods have been unsuccessful (Couteau 1971; Muller 1971), confirming the high luminosity ratio. With a separation of roughly 50 a.u., the period of this system is probably too long to account for any gross properties of the light curve, although tidal interaction may still contribute to the variation mechanism. Further details of this observation will be presented in a separate article.

Betelgeuse (α Ori) (fig. 1) was observed simultaneously in blue, green, and yellow bandpasses each 250 Å wide, in a red bandpass 500 Å wide, and later in the infrared at a wavelength of 1.0 μ. The results and their implications concerning models of this variable M3 supergiant will be discussed in a subsequent article. It appears clear, however, that (1) the diameter is slightly color-dependent; and (2) the object is limb darkened since the transform shows no trace of the dark and bright rings expected from a uniformly emitting disk.

The diameter of *o* Ceti (Mira) was visually estimated in April to be significantly larger than Pease's (1931) value of 0″.048. Observations are being continued to study the diameter, size fluctuations, and the possible presence of nonradial oscillations. The visual appearance of VY CMa also suggested a very large diameter.

The star μ Cas is a subdwarf binary system of interest in connection with the primordial helium abundance. The published photocentric orbit (Lippincott and Wyckoff 1964) contains insufficient information for a determination of Y from the mass by using quasi-homology relations since the absolute scale of the orbit is not known. Previous determinations of the orbit (Hegyi and Currott 1970) imply a very small primordial helium abundance, but suffer from large uncertainties. Faulkner (1971) has pointed out that a determination of Y to an accuracy of ± 0.1 requires that the semimajor axis (~1″.0) be known to within 3–4 percent. This accuracy is attainable from the speckle technique; however, when the observation was made under average seeing conditions, no binary companion brighter than $\sim m_v = +9$ could be detected within $1''.0 \gtrsim \rho \gtrsim 0''.015$ of μ Cas.

IV. DISCUSSION

The composite Fourier transform for an unresolved star has a bright central peak surrounded by a bell-shaped function and a weaker halo of noise. In most cases the profile of the bell-shaped function corresponds approximately to the theoretical profile, which Korff and Dryden (1972), in their random-walk analysis of the method described here, have determined to be the squared optical transfer function of the diffraction-limited aperture. However, the profile was found to vary appreciably during some nights as a function of telescope orientation, focus setting, and exposure time. Aberrations are believed to cause most of the observed variation, although they do not affect the method in a first approximation. Small telescopic aberrations may be thought of as a time-invariant component of seeing, but excessive wave-front distortion can affect the composite transform in two ways: (1) loss of temporal coherence from delayed portions of the wave front; and (2) geometrical ray deflection destroying the superposition in the image of contributions from all parts of the aperture. These effects were observed following severe temperature changes and at large zenith angles. Their influence is reduced considerably by use of a reference star in the data-reduction procedure.

The limiting magnitude for diameter determinations is presently on the order of +9 with good seeing conditions. The limiting magnitude of the speckle technique is determined by photon noise which affects the composite transform of underexposed films. With decreasing exposure, the bell-shaped "signal" function becomes buried in the halo of noise. Some improvement may be possible with better signal-to-noise by co-adding a larger number of transforms.

The measurements made thus far essentially confirm those of Michelson, Pease, Anderson, Merrill, and Evans, indicate no oblateness in the stars observed, and show apparent limb darkening for one star, α Ori.

Compared with other high-resolution techniques, speckle interferometry is characterized by relative ease of operation, a high data-recording rate, and two-dimensional data acquisition. More information may be obtained only when the object of interest and a suitable reference star are in the same isoplanatic patch, i.e., are sufficiently close together to be subject to identical wave-front deformation. In this situation the spread function is known and the production of a true "deblurred" image is theoretically possible by using deconvolution methods.

The technique is currently being applied to the detection of circumstellar shells in the infrared at 1.0 μ, stellar limb darkening in the visible and ultraviolet, size fluctuations of o Ceti, and observation of galactic nuclei. A television system is being developed to produce real time Fourier transforms at the telescope with improvement of signal-to-noise ratio and magnitude limit. In addition, the results indicate the feasibility of combining several telescopes into a large synthetic aperture system for extremely high optical resolutions.

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REFERENCES

Anderson, J. A. 1920, *Ap. J.*, **51**, 263.
Courtès, G. 1962, *C.R.*, **254**, 1738.
Couteau, P. 1971, private communication.
Evans, D. S. 1955, *M.N.R.A.S.*, **115**, 468.
Faulkner, J. 1971, *Phys. Rev. Letters*, **27**, 206.
Gaviola, E. 1948, *A.J.*, **54**, 155.
Hanbury Brown, R. 1968, *Ann. Rev. Astr. and Ap.*, **6**, 13.
Hanbury Brown, R., and Twiss, R. C. 1958, *Proc. Roy. Soc.* **248**, 199.
Hegyi, D., and Currott, D. 1970, *Phys. Rev. Letters*, **24**, 415.
Korff, D., and Dryden, G. 1972, *Journal Opt. Soc. Am.*, in preparation.
Labeyrie, A. 1970, *Astr. and Ap.*, **6**, 85.
Lippincott, L., and Wyckoff, S. 1964, *A.J.*, **69**, 471.
Merrill, P. W. 1922, *Ap. J.*, **56**, 40.
Michelson, A. A., and Pease, F. G. 1921, *Ap. J.*, **53**, 249.
Muller, P. 1971, private communication.
Pease, F. G. 1931, *Ergebn. Exakten Naturwiss.*, **10**, 84.
Rösch, J. 1958, *C.R.*, **247**, 422.
Schneiderman, A. 1972, private communication.
Texereau, J. 1961, *La Construction du Têlescope d'Amatuer* (Paris: Société Astronomique de France), p. 267.
Vaughan, A. H. 1971, private communication.