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SPECKLE INTERFEROMETRY: COLOR-DEPENDENT LIMB DARKENING EVIDENCED ON ALPHA ORIONIS AND OMICRON CETI*

D. BONNEAU AND A. LABEYRIE
Observatoire de Paris-92190-Meudon (France)
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ABSTRACT

Speckle-interferometry images of α Orionis and o Ceti, recorded with a television system on the 200-inch telescope, were studied visually as a preliminary reduction procedure. Both stellar disks have a limb-darkened profile which is appreciably wider in blue than in yellow and red light, suggesting a contribution of scattering phenomena in chromospheric opacity.

Subject headings: instruments — limb darkening, stellar

I. INTRODUCTION

Further speckle-interferometry observations (Labeyrie 1970; Gezari, Labeyrie, and Stachnik 1972) have been made at Mount Palomar. Because of the large (10^6) number of images recorded, mostly on video tape, a new processing technology is required for reducing the observation data. Such technology is being developed and should become usable in the near future.

However, we found it useful to perform a preliminary reduction of data concerning α Ori (Betelgeuse) and o Cet (Mira), for which peculiar color-dependence effects had been noticed in the speckle images ever since the time of their recording.

This reduction was achieved through visual analysis of both the recorded images and comparison data provided by simulation experiments. It has confirmed the initial impression, showing that the stellar profiles are wider at the blue end of the visible spectrum than in the red and near-infrared.

II. OBSERVING TECHNIQUE

In order to avoid the slight image degradation caused at Cassegrain focal positions by flexure of the telescope truss, we have now observed at prime focus. The optical attachment used (Labeyrie 1972) is similar to that previously described but incorporates a microscope lens with higher magnification for a similar resulting image scale of $1'' \text{ cm}^{-1}$. This lens, built by one of us, incorporates a field finder and has negligible geometric or chromatic aberrations from 3000 to 10,000 Å.

Interchangeably with the initial film recording system, we have used a television system working at the standard field rate of 50 s^{-1}, matching approximately the lifetime of seeing. The television camera is equipped with a silicon-intensified target tube (RCA type 4804) having nearly photon-limited performance. A $\frac{1}{2}$-inch video tape recorder (Sony CV 2100 ACE) records the video signal for subsequent analysis.

The television images can in principle be processed by using either Fourier or autocorrelation analysis. Devices capable of achieving this at sufficient speed, and possibly on-line, are (1) the TITUS, a light-valve cathode-ray tube using the Pockels effect (Marie 1969; Groh and Marie 1970); (2) electronic autocorrelators (Connes 1972); (3) high-speed digital computers (Schneiderman 1972). Partial tests were

* This article is based on observations made by R. Stachnik, D. Gezari, and the authors as Guest Investigators at the Hale Observatories.

made, with encouraging results, using the TITUS and also electronic correlation circuits.

The visual procedure used in the preliminary reduction discussed here consisted in playing back on a television monitor the recorded images, alternately with comparison images produced on a simulation bench. The simulator consists of the original recording system associated to a simulated telescope in the form of a lens (focal length 50 mm) suitably apertured in its front focal plane with an f3.3 centrally obstructed diaphragm. Stellar disks of various sizes are simulated by a series of pinholes mounted in front of a quartz iodine lamp bulb. The equivalent of a uniform and spatially incoherent stellar disk is obtained by using pinholes smaller than the tungsten filament and located very close to the bulb, without condenser or diffuser. A movable sheet of polyethylene reproduces the effects of atmospheric seeing.

The polyethylene was selected to give images of approximate size 1″, but its exact optical properties are of little importance as long as temporal coherence is preserved, since the statistics of speckle does not depend on the scatterer used (Enloe 1967; Gabor 1970; Korff, Dryden, and Miller 1972).

By switching repeatedly (every 3 seconds) the playback from stellar to simulation images, a rather accurate comparison can be made. Visual spectators find which pinhole size gives speckles best fitting the stellar appearance. The eye and associated brain perform relatively well in cases of a simple disk function convolved with the complicated speckle pattern. With binary stars such as β Cep, however, for which the companion is faint and spaced by several speckle grains, a trained eye fails to detect the companion in the images even though it does recognize the fringes in composite power spectra or even in single ones.

III. RESULTS

Unresolved stars exhibit speckle patterns very similar to simulation images of unresolved pinholes. With α Ori and o Cet both of particularly large apparent size, the speckles are immediately recognized as characteristic of a resolved star. The pinhole diameters giving the best fit at different wavelengths are listed in table 1.

TABLE 1

PINHOLE-FITTING VALUES OF STELLAR DIAMETERS

Wavelength (Å)	Diameter (″)
α Orions, 1972 September 9	
4220	0.069 ± 0.005
4880	0.067 ± 0.005
5700	0.055 ± 0.005
7190	0.052 ± 0.005
10400	⩽0.050*
o Ceti, 1972 June 25 (phase 0.09; $V = 4$)†:	
4500	0.070 ± 0.010
5150	0.057 ± 0.005
7500	0.051 ± 0.005
10400	⩽0.050*
o Ceti, 1972 September 29 (phase 0.38; $V = 7$)†:	
6700	0.062 ± 0.005
7000	0.058 ± 0.005
7500	0.055 ± 0.005

* From images recorded on film and Fourier-analyzed.

† Calculated from *Information Bulletin on Variable Stars,* UAI 513 (1971).

However, it was found that no pinhole image could reproduce exactly the more diffuse appearance of α Ori and o Cet speckles, especially in blue light. The residual difference found between speckles in stellar images and in the best-fitting pinhole images involves the intensity profile of speckle granules; in the case of pinhole images, the profile is found to be square with rounded edges and a slight median dip produced by a predictable contrast inversion effect. The α Ori and o Cet speckles have a more bell-shaped profile. The difference is most pronounced in blue light.

Limb darkening is the most probable cause for these observed differences. In fact, evidence for limb darkening was already reported in the case of α Ori: the visibility function obtained by laser-processing speckle images recorded on film did not feature the secondary ring which should have been present in the case of a uniform-disk object (Gezari *et al.* 1972).

In blue light as well as in red light, the images also suggest bell profiles for the intensity of both stellar objects. In red light, however, the half-intensity width is less (as suggested by table 1) and the summit of the bell tends to be more square-profiled than in blue light, particularly in the case of α Ori. Comparison of the o Cet data in red light at the two different dates shows a possible increase in diameter.

The figures given in table 1, which correspond approximately to stellar diameters at half-intensity points, are larger than those given by Pease (1931). However, the discrepancy should not be considered as very significant, nor as evidencing a change in stellar diameter, for the following reasons: (1) Pease observed in unfiltered light; (2) the position of the first visibility zero, on which Pease's diameters were based, is probably a bad indicator of half-intensity diameters when limb darkening is present; (3) Pease's observation of the visibility zero was difficult since no secondary maximum was seen at larger baselines.

Several emission or scattering processes in stars can produce polarized light with apparent orientation either radial (in a circumstellar shell) or nonradial (on magnetic spots). We have attempted, unsuccessfully at this stage, to resolve such features by inserting a polarizer in the optical beam. Using lock-in detection techniques, much sensitivity could be gained in such observations.

IV. CONCLUSION

Few models of cool stars have been published, probably because of the extreme complexity of transfer phenomena in extended stellar atmospheres containing not only atoms and molecules but also perhaps solid grains assembled in shell or disk structures. Clearly, the limb-darkening effects to be expected from such objects depend greatly on the relative contribution of absorption and scattering phenomena, such as Rayleigh, Mie, or resonance scattering, in their atmospheres. However, spectroscopy has not given much information on the scattering properties of stellar atmospheres.

On high-resolution images, circumstellar envelopes in which scattering is predominant should be expected to appear as a larger blue halo superposed on the reddened and smaller central disk, since continuum scattering generally decreases at increasing wavelengths. With resonance scattering, invisible shells could possibly become visible at some sharply defined wavelengths.

Because of the larger blue diameter found, the above results do suggest that continuum scattering has an appreciable contribution in the case of α Ori and o Cet.

A more quantitative reduction technology is clearly needed to confirm and prolongate the results given in this article. In the absence of a well-defined stellar limb, as is apparently the case in α Ori and o Cet, little descriptive value can be attached to diameter determinations. What is needed is intensity profiles, and adequate analysis can probably provide this information.

The television system coupled with a TITUS processor has some analogies with the device proposed by Babcock (1953) for compensating atmospheric seeing, and we have wondered if it could be used according to Babcock's method. Indeed, this method is theoretically superior to speckle interferometry for producing images when a reference star is located near the object. Unfortunately, it still seems difficult, with existing technology, to map the optical wave and correct it for the defects of phase and amplitude which both affect the image.

We wish to thank R. V. Stachnik and D. Y. Gezari for their participation in these observations. Geographic circumstances have so far prevented them from studying the recorded images, and they have asked us to submit this report separately.

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