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The Angular Diameter of Betelgeuse

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Summary. We report measurements of the diameter of Betelgeuse using Labeyrie's speckle interferometer attached to the 6-m soviet telescope and the 3.6-m ESO telescope. The TiO related diameter variations evidenced in this paper are not consistent with the effective temperature $T_{\mathrm{eff}} = 3900$ K proposed by Tsuji from model fitting to the observed energy distribution; this discrepancy is discussed. No other variation of diameter, either with wavelength or with time is meaningful within the range of errors.

Key words: star: diameter – cool stars – stellar atmosphere

I. Introduction

The high angular resolution achieved by interferometric methods of observation can contribute in a decisive way to our understanding of the atmospheric physics of cool stars. Indeed, these methods are now able to provide direct information about the geometrical structure of the atmosphere of evolved giants or supergiants, and to give a determination of the effective temperature. Moreover, a marked improvement in the signal to noise ratio should make it possible to study the center to limb darkening and its dependence with wavelength.

This paper reports Speckle interferometric observations of Betelgeuse (αOri, M1 Ib). We observed it:

(i) to estimate the upper limit in effective temperature of the TiO-related diameter variations which we discovered for Mira (Labeyrie et al., 1977), and

(ii) because its effective temperature is controversed: Tsuji (1976b) proposed a relatively high value $T_{\mathrm{eff}} = 4000$ K; he gave a detailed discussion of cooler determinations in the literature.

Observations with the 6-m soviet telescope at Zelentchuk and with the 3.6-m ESO telescope are reported in Sect. II, as well as a brief description of the data processing. Diameter measurements are given and discussed in Sect. III. The concluding section summarizes our results.

II. Observations and Data Processing

Observations were carried out with the Digital Speckle interferometer (Blazit et al., 1977) attached at the prime focus of the 6-m telescope of the Special Astrophysical Observatory (Zelentchuk, USSR), and of the 3.6-m telescope of the European Southern Observatory (La Silla, Chile). Compensation for the atmospheric dispersion as well as selection of the wavelength and of the bandwidth of observation is provided by a holographic grating located in the image plane. Stellar images were recorded by a photon counting TV camera on video tape with 20 ms exposure time. At λ 5500 Å the pixel size was respectively 2.8 m″ and 6.5 m″ for the 6-m and the 3.6-m telescopes, amounting respectively to 14 % and 20 % of their Airy disc. Data were processed on line, using the digital correlator (Blazit, 1976) and again back in the laboratory as described in Bonneau and Foy (1980). Angular diameters were determined following the same procedure as described in Labeyrie et al. (1977).

Table 1. New measurements of the angular diameter of Betelgeuse. Column heading are self explanatory

Date	Telescope	λ(Å)	$\Delta\lambda$(Å)	$\varnothing$(m″)	$\Delta\varnothing$(m″)
Nov. 9, 1978	3.6-m ESO	4050	150	45	4
		7100	50	54	3
		7150	20	67	4
Feb. 22, 1979	6-m SAO	5750	84	62	3
		5870	16	62	3
		7520	16	50	4
		7730	84	62	2

Table 1 lists the parameters of the observations: data and place of observation (Columns 1 and 2), wavelength and bandwidth (Columns 3 and 4), measurements of angular diameters assuming a uniform disc and standard deviations σ (Columns 5 and 6).

We assumed the 4σ error bar is defined by the inner and outer envelopes of the observed autocorrelation profile by the theoretical ones for a uniform disc. In the absence of reliable information about limb darkening for cool stars we find it preferable to use only uniform-disc angular diameters.

III. Results and Discussions

The averaged value of diameter measurements in Table 1 is $\langle\varnothing\rangle = 57 \pm 8$ m″; the weighted average is not different: 58 m″. The mean of error bars is 3 m″.

Our mean value of the diameter of Betelgeuse is relatively large compared to previous measurements, down to 34 m″ by Pease

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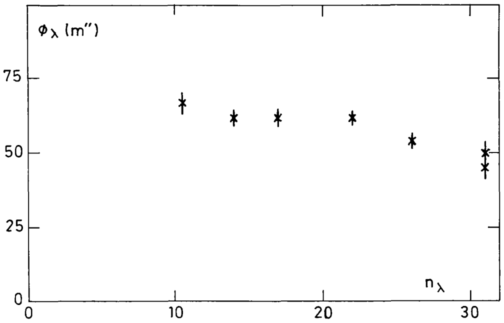

Fig. 1. Angular diameter of Betelgeuse measured at different wavelengths $\varnothing_\lambda$, versus the number of the layer n_λ (defined by $\tau_{\mathrm{TiO}}=1$) in the model atmosphere ($T_{\mathrm{eff}}=3400$ K, $\log g=0.5$, $\xi=3$ km s^{-1}). (1 m″ $=10^{-3}$″)

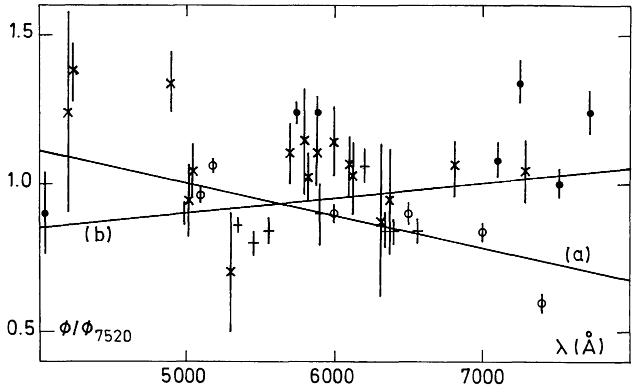

Fig. 2a and b. Uniform disc angular diameter of Betelgeuse normalized with respect to the diameter at λ7520 Å ($\varnothing_{7520}=50$ m″) versus wavelength. Symbols refer to: ● this paper, ○ Lynds et al. (1976) and Walter and Worden (1980), + Roddier et al. (1981), and × other measurements reported by White (1980). The straight lines are linear regressions: **a** $\varnothing/\varnothing_{7520}=-10^{-4}\,(\pm 3\;10^{-6})\,\lambda(\text{Å})+1.49\,(\pm 0.02)$ with a correlation coefficient $r=-0.48$. Excluding data from Lynds et al. and from Welter and Worden them would lead to: **b** $\varnothing/\varnothing_{7520}=5\;10^{-5}\;(\pm 6\;10^{-6})\,\lambda(\text{Å})+0.65\,(\pm 0.03)$ with $r=0.23$

(Sanford, 1933); but diameters as large as 69 m″ have been reported (Bonneau and Labeyrie, 1973). We have checked the significance of averaging our measurements. The observed sample has a probability of less than 10^{-3} to be selected from a normal population of values with a mean value $\varnothing_0=57$ m″ and a standard deviation $\sigma=3$ m″. We conclude that the scatter in our diameter measurements has a physical origin. This intrinsic scatter may be related to the TiO spectrum, since we discover a strong relation between this spectrum and the observed diameter of Mira (Labeyrie et al., 1977). In Bonneau et al. (1982), we gave a detailed discussion of the interpretation of diameter measurements in terms of Tsuji's model atmospheres. We propose in this paper a similar analysis of the angular diameters given in Table 1. We do not consider observations by Bonneau and Labeyrie (1973) because they used relatively large bandwidths (200 Å) covering spectral features formed at very different optical depths. Using:

(i) oscillator strengths of TiO band α, α', γ, γ', δ, and φ, and opacities per TiO molecule tabulated as function of temperature and wavelength (Collins, 1975);

(ii) model atmospheres kindly communicated by Tsuji (1973, 1976a), we have computed the geometrical depth for which the optical depth in TiO features reaches unity at the observation wavelength.

These geometrical depths are strongly dependent on the atmospheric parameters gravity and turbulent velocity; instead, we use the corresponding number n (with $n=-5\log\tau+31$) of the atmospheric layer in Tsuji's models which is much more slowly varying. Figure 1 displays how n relates with the observed diameter at each wavelength, where n is computed from the model (effective temperature in K, gravity in cm^2 s^{-1}, turbulent velocity in km s^{-1}) $=(T_{\mathrm{eff}}, g, \xi)=(3400, 3, 3)$.

We showed in Bonneau et al. (1982), that n_λ (i.e. the geometrical depth in the atmosphere) and the angular diameter $\varnothing_\lambda$ are linearly dependent, as far as the hypothesis of a plane parallel atmosphere is valid. A linear regression in Fig. 1 leads to $\varnothing_\lambda(\mathrm{m}'')=-0.92\,(\pm 0.15)\,n_\lambda+79.5\,(\pm 3.4)$, with a correlation coefficient $r=-0.87$. The distribution of points in the plane (n_λ, $\varnothing_\lambda$) of Fig. 1 has a very low probability ($\simeq 10^{-8}$) to be a random one. The angular diameter resulting for the atmospheric layer $\tau_{\mathrm{continuum}}=1$ ($n_\lambda=31$) is $\varnothing_c=51\pm 8$ m″.

The linear regression is not very sensitive to reasonable changes in the atmospheric parameters adopted. Indeed it is $\varnothing_\lambda(\mathrm{m}'')=-0.91\,(\pm 0.23)\,n_\lambda+82.0\,(\pm 5.9)$ and $r=-0.76$ with $(T_{\mathrm{eff}}, g, \xi)=(3400, 10, 3)$ and it is:

$\varnothing_\lambda(\mathrm{m}'')=-0.75\,(\pm 0.08)\,n_\lambda+71.4\,(\pm 1.4)$ and $r=-0.94$ with $(T_{\mathrm{eff}}, g, \xi)=(3200, 10, 3)$.

Here it is interesting to note that Tsuji (1976b) gave a detailed discussion to justify a significantly higher effective temperature for Betelgeuse: $T_{\mathrm{eff}}=3900$ K. But with models as hot as proposed by Tsuji, we derive that there must not be a dependence of the diameter on the TiO spectrum: even at the strongest TiO features, the atmosphere is optically thin. This would conflict with the observed scatter in the measurements as well as the strong correlation between $\varnothing_\lambda$ and n_λ found using cooler models. Several ideas can be proposed to solve this problem:

1. Our interpretation of the relation ($\varnothing_\lambda$, n_λ) is spurious: $\varnothing_\lambda$ is related to n_λ not only because of TiO features, but also because of another physical reason. The effect of the circumstellar dust shell must be examined. If the scattering coefficient of the dust is added to the absorption coefficient by TiO molecules present in the circumstellar shell, then the total absorption coefficient could be greater than unity. In this case, we should observe the inner layers of the circumstellar envelope where the density is low enough to allow a small but significant dependence of the observed diameter on the TiO spectrum. Then, there is no more conflict with the high effective temperature proposed by Tsuji (1978) and the lower temperature from atmospheric models compatible with the TiO effect on the directly measured angular diameter.

Also, it is interesting to note that the smallest value measured for the angular diameter is consistent with the value $\varnothing_{ud}=38\pm 3$ m″ derived by Tsuji (1978) from photometric data. However these measurements do not support the hypothesis of a circumstellar shell optically thick in the visible.

The observations from Bonneau and Labeyrie (1973) and more recently from Welter and Worden (1980), suggested that the diameter of Betelgeuse is an inverse function of the wavelength presumably because scattering by dust or molecules is more efficient in the blue than in the red. This idea cannot help in the interpretation of Fig. 1: our smallest diameter at λ4100 Å does not significantly differ from that obtained at λ 7520 Å. We note that for Mira, we measured also the smallest diameter near λ 4000 Å (Bonneau et al., 1982).

Figure 2 shows the diameter measurements of Betelgeuse as a function of the wavelength; here diameters are normalized with respect to the diameter in the continuum at λ 7520 Å (this paper), in order to underline a possible correlation between these quantities. Now measurements are from the compilation by White (1980), from Welter and Worden (1980), Roddier et al. (1981), Ricord et al. (1981), and from this paper. It is clear, that there is no trend in Fig. 2 (correlation coefficient $r=-0.48$, or $r=-0.23$ excluding measurements from Welter and Worden and from Lynds et al.), except for the only sets from Welter and Worden and from Lynds et al. Therefore, we do not believe that within the error bars, the angular diameter of Betelgeuse increases towards short wavelengths in the continuum. We note in Fig. 2 that the largest diameters were measured in large bandwidths including strong absorption features (Ca I λ 4226 Å, Hβ λ 4861 Å, and TiO λ 7140 Å).

White (1980) claimed that the spread in diameter measurements is due to periodic variations of ϕ with time. He used a plot of ϕ versus the phase φ of Betelgeuse at the time of the observations; the phase was calculated from the elements given by Sanford (1933). White emphasized the feeling of a periodic variation by doubling the plot along the phase axis. In fact, we checked that there is no significant difference between the fit to the data of a sine curve ($\varnothing=8\sin(2\pi\varphi+\pi/2)$), of a serrated curve ($\varnothing=53.3\varphi+28$ for $0.15<\varphi<0.45$ and $\varnothing=-22.9\varphi+62.3$ for $0\leqq\varphi\leqq0.15$ and $0.45\leqq\varphi\leqq1.0$) or of a horizontal straight line. Errors in standard deviation of the fitting at the 1σ confidence level are respectively $5.9<\sigma<8.4$, $5.6<\sigma<8.0$, and $6.9<\sigma<9.9$: they largely overlap. The determination of the phase from the epoch 1928 is highly uncertain since Betelgeuse is a semiregular variable. An investigation such as proposed by White should simultaneous utilize photometric, spectroscopic, and interferometric observations.

2. The effective temperature of Betelgeuse could be cooler than 4000 K. It is difficult to assume $T_{\mathrm{eff}}\lesssim 3800$ K on the basis of Tsuji's model atmosphere (1976b). He excluded $T_{\mathrm{eff}}=3600$ K because of the energy distribution around λ 1 µm (in spite of a better fit in the visible spectral range than with hotter models). Such high temperatures are not consistent with our diameter measurements. Our determination $\varnothing_c=51\pm8$ m″ leads to $T_{\mathrm{eff}}=3250^{+300}_{-120}$ K, assuming the apparent bolometric magnitude corrected for interstellar extinction $m^0_{\mathrm{bol}}=-1.7$ and the limb darkened to equivalent uniform disc $\varnothing_{LB}/\varnothing_{UD}=1.12$ (Tsuji, 1976b); adopting our smallest diameter measurement ($\varnothing_{4000}=45$ m″) does not change significantly the temperature: $T_{\mathrm{eff}}=3460$ K.

3. Something is missed in model atmosphere calculations. For instance, most of the models for cool stars are plane parallel atmospheres. Tsuji (1976a) pointed out that this hypothesis is no longer valid if the extension of the atmosphere is as large as 20 % of the stellar radius; in fact, it happens to be at least 30 % according to our measurements or those of Roddier et al. (1981). The effect of sphericity is to decrease the temperature in the outer atmospheric layers with respect to the case of a plane parallel atmosphere. Therefore we have to expect greater optical depths at strong TiO feature wavelengths than predicted from Tsuji's models: the diameter will be dependent on the TiO spectrum at hotter T_{eff} than found in this paper.

Model atmospheres do not take into account the extended atmosphere or circumstellar shell surrounding Betelgeuse. This shell is evidenced in the KI line at λ 7700 Å (Bernat and Lambert, 1975; Honneycutt et al., 1980); the circumstellar dense regions close to the stellar surface could cause the large diameters observed at wavelengths of CaI (λ 4226 Å), Hβ, and Hα (Goldberg et al., 1981), and likely cause the large component observed in the continuum by Ricord et al. (1981). The resulting greenhouse effect could provide the flux excess near λ 1 µm which raised theoretical energy distribution fitting towards high temperatures.

4. Schwarzschild (1975) showed that giant convective cells in small number should induce large inhomogeneities in effective temperature at the surface of cool supergiants. Due to the effect of these inhomogeneities, we could observe different parts of the stellar disc according to the wavelength.

Point 3 should be cleared up by improvements in model atmosphere calculations; but observational contributions are possible: (i) by observations with very narrow bandwidths centered on strong absorption features [as done for Hα by Goldberg and his coworkers (1981)] and (ii) by studying the properties (mainly the wavelength dependence) of the inner circumstellar shell discovered by Ricord et al. (1981). About point 4 the signature of the giant convective cells predicted by Schwarzschild in the power spectrum of Betelgeuse could be displayed by observations with Labeyrie's two telescope interferometer at CERGA.

Conclusion

The new measurements of the angular diameter of Betelgeuse reported in this paper, confirm the marginal TiO-related diameter variations found by Lynds et al. (1976). These variations raise the problem of the effective temperature of Betelgeuse; indeed the value $T_{\mathrm{eff}}=3900$ K proposed by Tsuji (1976b) is so high that even the strongest TiO features are not optically thick: therefore we should not detect the variations which we report here. Also, it appears that there is no meaningful variation of the diameter with wavelength. White (1980) proposed that the diameter of Betelgeuse shows periodic temporal variations related to the photometric and radial velocity variations evidenced by Sanford (1933). We found that these variations are not meaningful, within the range of errors. There is no evidence for inhomogeneities on Betelgeuse's disc from our data.

From the diameter measurements at several wavelengths, we derived the minimum angular diameter for the atmospheric layer $\tau_{\mathrm{continuum}}=1$: $\varnothing=51\pm8$ m″; the resulting effective temperature is: $T_{\mathrm{eff}}=3250^{+300}_{-120}$ K. This value of T_{eff} is low enough to understand the TiO related variations in the measured diameters, but it is too low to allow a theoretical fit of the red and near infrared energy distribution of αOri (Tsuji, 1976b).

Further work about the diameter of Betelgeuse should concern:

(i) diameter measurements in the continuum to show an eventual variation with wavelength due to scattering in the stellar atmosphere as suggested by Tsuji (1978), and to derive an empirical limb-darkening which would provide information about the inner atmospheric structure;

(ii) diameter measurements with narrow spectral bandwidths to study the outer atmospheric layers;

(iii) correlation between photometric, spectrometric, and interferometric measurements to give evidence of eventual temporal variations in diameter;

(iv) continued effort to detect fine morphological details e.g. granulation and oblateness, which multi-telescope interferometers can in principle reveal.

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References

Bernat, A.P., Lambert, D.L.: 1975, *Astrophys. J.* **201**, L153

Blazit, A.: 1976, Thesis, Université de Paris VII

Blazit, A., Bonneau, D., Koechlin, L., Labeyrie, A.: 1977, *Astrophys. J.* **217**, L79

Bonneau, D., Foy, R.: 1980, *Astron. Astrophys.* **92**, L1

Bonneau, D., Foy, R., Blazit, A., Labeyrie, A.: 1982, *Astron. Astrophys.* **106**, 235

Bonneau, D., Labeyrie, A.: 1973, *Astrophys. J.* **181**, L1

Collins, J.G.: 1975, Thesis, Indiana University

Goldberg, L., Hege, E.K., Hubbarb, E.N., Strittmatter, P.A., Cooke, W.J.: 1981, Proceedings of second Cambridge workshop on cool stars, stellar systems, and the Sun (in press)

Honeycutt, R.K., Bernat, A.P., Kephart, J.E., Cow, C.E., Stanford II, M.T., Lambert, D.L.: 1980, *Astrophys. J.* **239**, 565

Labeyrie, A., Koechlin, L., Bonneau, D., Blazit, A., Foy, R.: 1977, *Astrophys. J.* **218**, L75

Lynds, C.R., Worden, S.P., Harvey, J.W.: 1976, *Astrophys. J.* **207**, 174

Ricord, G., Aime, A., Vernin, J., Kadiri, S.: 1981, *Astron. Astrophys.* **99**, 232

Roddier, C., Roddier, F., Vernin, J.: 1981, Proceedings of the ESO Conference on Scientific importance of high angular resolution at infrared and optical wavelengths 165

Sanford, R.F.: 1933, *Astrophys. J.* **77**, 110

Schwarzschild, M.: 1975, *Astrophys. J.* **195**, 137

Tsuji, T.: 1973 (private communication)

Tsuji, T.: 1976a, *Proc. Japan Acad.* **52**, 183

Tsuji, T.: 1976b, *Publ. Astron. Soc. Japan* **28**, 567

Tsuji, T.: 1978, *Publ. Astron. Soc. Japan* **30**, 435

Welter, G.L., Worden, S.P.: 1980, *Astrophys. J.* **242**, 673

White, N.M.: 1980, *Astrophys. J.* **242**, 646