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LOWER ATMOSPHERE CHANGES INFERRED FROM VARIATIONS IN BETELGEUSE'S LINEAR POLARIZATION

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Variations in Betelgeuse's linear polarization were intensively monitored over the nearly eight-month interval which comprised the 1980–81 observing season. As was the case in the preceding observing season, significant ordered (as opposed to stochastic) polarization changes were detected. These variations are explained as being due to the waxing and waning, and motion of large-scale elements of the star's lower atmosphere, and are likely to be a manifestation of nonradial pulsations.

Key words: linear polarization—late-type supergiants—nonradial pulsations—convection

I. Introduction

Observations of the semiregular (SRc), late-type supergiant Betelgeuse (α Orionis, M2 I*ab*) over the course of the 1979–80 observing season offered convincing evidence for ordered (as opposed to stochastic) linear polarization variations (Hayes 1980; henceforth referred to as Paper I). This report will be devoted to the changes in the amount (P) and direction (θ) of Betelgeuse's linear polarization which occurred over the course of the immediately succeeding (1980–81) observing season. This nearly eight-month survey was motivated by a desire to determine the mechanism(s) responsible for previous reports of polarization variability in this star. As will be developed, the observations being reported here have contributed toward such a determination.

II. Observations

Like the 1979–80 survey, which formed the basis of Paper I, the polarization measurements being reported here were carried out at the Cassegrain focus of the 61-cm telescope at Columbia University's Harriman Observatory. The same wide-band (B) filter and essentially the same polarimeter, ancillary equipment, and observing procedures were used as in the preceding observing season. The polarimeter consists of a suitably peaked quarter-wave plate, a Pockels cell, a Polaroid analyzer, filter, and photomultiplier. Pulsed counting techniques were used. Further details on the polarimeter and its operation are provided by Hayes (1975, 1978).

During the course of these observations, several standard test stars were monitored for the purpose of gaining an estimate of instrumentation precision. One-sided χ^2 tests were carried out to gauge the variability of the observed Stokes parameters $Q = P \cos 2\theta$ and $U = P \sin 2\theta$ in comparison with that expected from photon statistics. These tests compared the sample variances derived from the scatter of the test-star data with the theoretical variances expected from Poisson photon-count statistics. These tests established that photon-count statistics provide a quantitative estimate of instrumental error over the course of this observing interval. Subsidiary evidence for instrumentation precision over the interval October–November 1980 appears in Hayes (1981*a*, 1981*b*).

The 62 observations of Betelgeuse carried out over the 233-day interval 1980 September 7–1981 April 28 are listed in Table I, with the amount and direction of polarization being expressed in percentages and equatorial coordinates, respectively. As was the case for the preceding observing season, all observations have Poisson photon-count standard deviations of 0.015% for P and for the two Stokes parameters. (The photon-count errors always exceeded the contribution of sky background and any moonlight.) The standard deviation of θ is given by $28\overset{\circ}{.}7(\sigma_p/P)$. Even a cursory scan of Table I reveals overwhelming evidence for statistically significant polarization variations.

The observations being reported here (the 1980–81 results), as well as those reported in Paper I (the 1979–80 results), are plotted in the equatorial reference frame in Figure 1. The 1979–80 observations are plotted for purpose of comparison, and for the information that may be adduced from data obtained over two successive observing seasons. This figure reveals that ordered (as opposed to stochastic) polarization changes occurred over the 1980–81 season. This result confirms the ordered structure of polarization changes over the 1979–80 season reported in Paper I.

An estimate of the interstellar polarization is necessary before one may gauge the polarization intrinsic to this star. Using their own multicolor polarimetry data and that provided by Serkowski; Tinbergen, Greenberg, and de Jager (1981) have deduced a value for the interstellar component of Betelgeuse's polarization ($P \simeq 0.27\%$, $\theta \simeq 156°$) at an earlier epoch. (In addition to an invariant interstellar component, there may also be a

Table I

Polarization Degree and Position Angle of Betelgeuse Over the 1980-1981 Observing Season

Day #	Date (UT)	P (%)	θ (deg.)
1	1980 Sep 07	0.11	179.8
2	1980 Sep 08	0.09	176.5
3	1980 Sep 09	0.11	2.8
5	1980 Sep 11	0.09	3.6
10	1980 Sep 16	0.11	7.8
13	1980 Sep 19	0.10	12.5
14	1980 Sep 20	0.10	12.7
26	1980 Oct 02	0.13	42.8
32	1980 Oct 08	0.20	50.5
33	1980 Oct 09	0.17	53.2
34	1980 Oct 10	0.22	57.2
44	1980 Oct 20	0.35	62.6
46	1980 Oct 22	0.36	64.9
54	1980 Oct 30	0.47	67.9
55	1980 Oct 31	0.45	68.0
58	1980 Nov 03	0.50	69.5
61	1980 Nov 06	0.50	69.9
68	1980 Nov 13	0.52	75.0
72	1980 Nov 17	0.53	75.8
85	1980 Nov 30	0.59	85.5
90	1980 Dec 05	0.61	86.0
91	1980 Dec 06	0.60	88.9
92	1980 Dec 07	0.63	89.7
98	1980 Dec 13	0.65	91.4
100	1980 Dec 15	0.67	90.7
103	1980 Dec 18	0.69	95.1
116	1980 Dec 31	0.82	97.7
119	1981 Jan 03	0.81	102.4
122	1981 Jan 06	0.84	105.2
124	1981 Jan 08	0.83	103.2
125	1981 Jan 09	0.83	104.2
128	1981 Jan 12	0.84	104.8
129	1981 Jan 13	0.86	104.4
131	1981 Jan 15	0.84	109.4
132	1981 Jan 16	0.86	108.7
138	1981 Jan 22	0.87	110.1
139	1981 Jan 23	0.84	109.6
140	1981 Jan 24	0.85	110.7
144	1981 Jan 28	0.84	112.2
147	1981 Jan 31	0.85	110.3
148	1981 Feb 01	0.85	113.4
153	1981 Feb 06	0.84	114.7
156	1981 Feb 09	0.84	113.1
160	1981 Feb 13	0.89	113.5
161	1981 Feb 14	0.88	116.7
172	1981 Feb 25	0.84	120.8
175	1981 Feb 28	0.84	120.3
187	1981 Mar 12	0.73	122.5
188	1981 Mar 13	0.75	124.7
189	1981 Mar 14	0.74	122.4
191	1981 Mar 16	0.67	124.0
198	1981 Mar 23	0.67	124.9
199	1981 Mar 24	0.63	124.2
202	1981 Mar 27	0.65	124.9
203	1981 Mar 28	0.63	125.2
204	1981 Mar 29	0.63	124.3
207	1981 Apr 01	0.60	125.3
211	1981 Apr 05	0.63	126.9
214	1981 Apr 08	0.61	126.0
215	1981 Apr 09	0.61	127.9
217	1981 Apr 11	0.60	127.6
234	1981 Apr 28	0.59	127.8

moderate circumstellar component which would be expected to vary over relatively long time scales.)

It is instructive to compare the last observations of the 1979–80 observing season (1980 April 17) with the first observations of the 1980–81 season (1980 September 7). When one considers the long temporal differences (143 days), these two observations have a relatively small polarization difference (0.31%). When one also considers the comparative quiescence of polarization in February, March, and April of 1980 (consult Paper I for details), as well as the dearth of large polarization variations that occurred in September 1980, then it would appear that relatively slight polarization changes occurred over the interval May through August 1980, when Betelgeuse could not be monitored.

The data being presented here suggest the occurrence of two separate events. Supportive evidence for such a suggestion includes the following: the obvious differences in the morphology of the 1979–80 and the 1980–81 observations, and the fact that there was an interregnum during which the polarization appears to have reverted back to a value compatible with the estimated interstellar value. The occurrence of two separate events is consistent with Tinbergen et al. (1981) finding that polarization changes in Betelgeuse occurred over intervals of the order of one year. Their finding was based on observations spanning several observing seasons at an earlier epoch. These time scales bear resemblance to the 200- to 400-day mean cycle time of Betelgeuse's short-term photometric variations reported by Stothers and Leung (1971).

III. Discussion

Reasons for believing that these polarization variations arise from changes in the lower atmosphere—either directly through changes in the photosphere, or indirectly through changes in the illumination of circumstellar material—have already been discussed in Paper I. Stellar polarization is only expected if there is a mechanism for its production and a concomitant asymmetric atmosphere (a symmetric atmosphere would have no net polarization). Harrington (1969, 1970) has proposed that Rayleigh scattering would provide an efficient mechanism for producing polarization in the lower atmospheres of late-type stars; while Serkowski (1971) has shown that Betelgeuse's polarization shows both a Rayleigh scattering and a dust component.

A global nonradial pulsation was considered as a possible mechanism for providing the requisite asymmetry. The polarization changes induced by nonradial pulsations have been considered by Stamford and Watson (1980). (While their work was specifically directed toward early-type stars, their general results would also be expected to apply insofar as they are a purely geometrical manifestation of nonradial pulsations.) Consider a

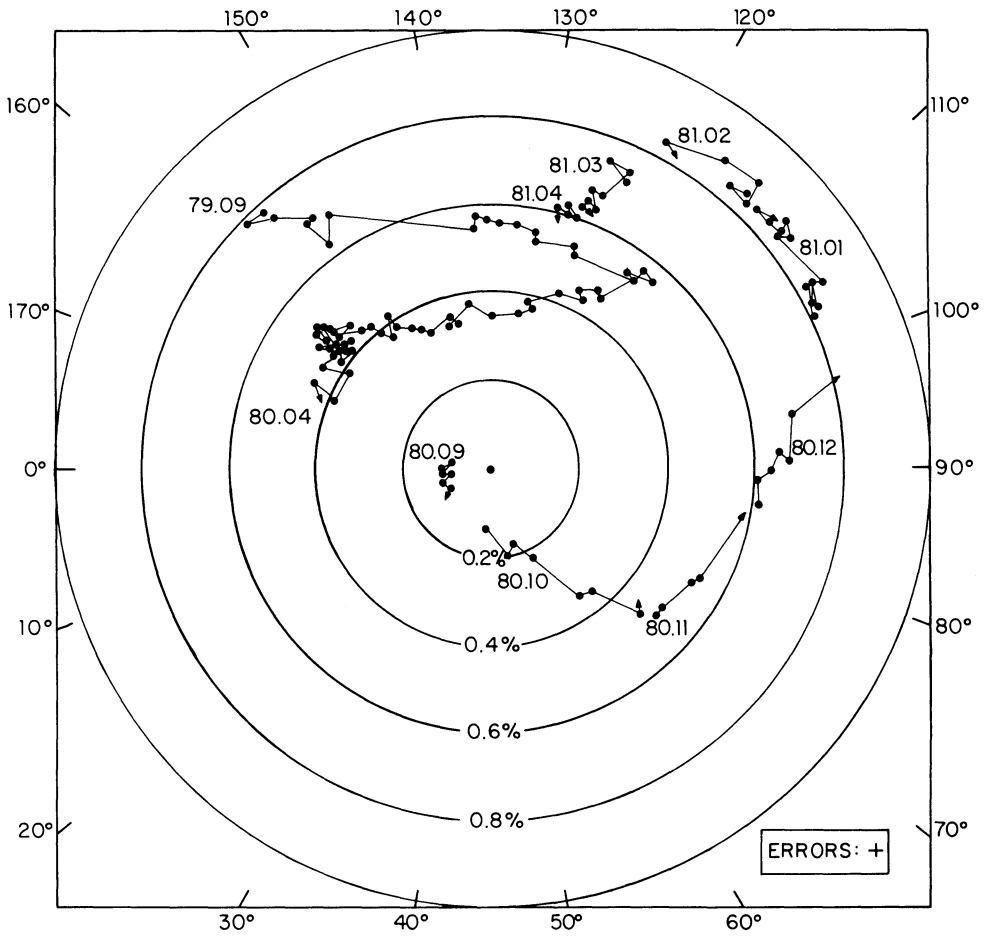


FIG. 1—Plot of Betelgeuse polarization observations obtained over the 1980–81 and the 1979–80 observing seasons. The polarization is plotted in the equatorial reference frame, where the distance of each data point from the origin is the percentage P and the angular coordinate is the double position angle 2θ. (The Q and U Stokes parameter axes are aligned along directions 0°–90° and 45°–135°, respectively.) The 1980–81 observations are specifically denoted by month and year; the 1979–80 observations (September 1979 through April 1980) are presented as one continuous segment. The cited errors are the 2σ standard deviations derived from Poisson photon-count statistics.

global non-radial oscillation corresponding to an arbitrary spherical harmonic distortion of degree (ℓ) and order (m) of a star whose equilibrium structure is considered to be spherically symmetric. The net polarization would not be expected to vary for either the $\ell = 0$ spherical harmonic (radial motion), or for any of the $\ell = 1$ spherical harmonics (for an incompressible star, dipole nonradial motion corresponding to side-to-side stellar motion); since neither of these motions would distort the star's spherical shape. All the axisymmetric $m = 0$ oscillations can likewise be discounted, since in this case any polarization variations would be manifested as collinear changes in the Stokes parameter (Q,U) frame. Next consider $|m| > 0$, where the oscillations are traveling waves. A traveling wave would cause the end of the observed polarization vector to rotate in the (Q,U) frame; in general tracing out elliptical figures whose configurations depend on ℓ, m and i (the stellar inclination), but which are all centered on a common point. These spherical harmonics can likewise be discounted, since Figure 1 shows that the 1979–80 and the 1980–81 observations are not centered on a common point in the (Q,U) plane. Therefore a single global pulsation mode is not consistent with Betelgeuse's polarization variations. (While a single mode is ruled out, it may still be possible to fit the data with several simultaneously excited modes.)

Instead of global changes, consider local changes as an alternative explanation. Specifically consider a surface element which has the following properties: a polarization whose magnitude is controlled by the waxing and waning of the element; and, a polarization position angle which reflects changes in the orientation of the element (there may also be a component due to changes in the element's configuration). Orientation changes could be due to the rotation of an otherwise stationary element;

and/or, it could be a manifestation of the element's movement over the stellar surface (straight line movements, per se, would not be expected to induce position angle changes). Parenthetically, Coriolis forces would not account for the observed position angle changes, since it would take at least half the stellar rotation period for these forces to cause a particle to complete a circular path. (A credible estimate of this star's rotation period would be $\geq$ 9 years (Paper I).)

Lower atmosphere changes could account for the 1980–81 observations in the following manner. As already noted, the polarization was relatively quiescent over the eight-month interval February–September 1980. But the polarization showed a nearly collinear change which commenced in September 1980 and continued over the following month. This quasi-collinear polarization change is interpreted as arising from the growth of a surface feature. Polarization changes over the interval November 1980 through February 1981 are interpreted as mainly arising from changes in this element's orientation. Polarization changes over March and April of 1981 suggest that a decrease in the strength of the surface feature has commenced. The main features of the 1979–80 observations could be explained by an element whose strength was decreasing as its orientation changed.

It still remains to specify the mechanism responsible for producing such surface features and their concomitant changes. Consider that local (as opposed to global) nonradial pulsations provide the essential explanation. Such pulsations would provide a means of producing the requisite asymmetry, and would not be inconsistent with the polarization variations being reported here. Because of these reasons, local nonradial pulsations are favored as an explanation. An allied explanation of these observations would be that of convection. Schwarzschild (1975) has postulated that late-type supergiants have large-scale convective cells. In addition to up and down motion, these cells may also be expected to rotate as well as to move as a whole across the stellar surface, although quantitative estimates of these velocities do not appear to be available. But it is important to note that the difference between nonradial pulsations and convection is actually only one of semantics. Cox (1976) has noted that from the standpoint of stellar oscillation theory, convection is presumably a (nonlinear) manifestation of dynamically unstable gravity modes. In summation, it would appear that the polarization variations being reported here can best be explained by some type of nonradial pulsations.

It should be noted that the large-scale convective cells postulated by Schwarzschild (1975) are not consistent with the observations being reported here. Schwarzschild (1975) has roughly estimated that at any one time about 90 such elements would occupy the total surface area of a red supergiant. But such a large number of cells is incompatible with the ordered polarization changes being reported here. Such ordered changes imply the presence of at most a few cells at any one time. Therefore the type of large-scale convection cells envisaged by Schwarzschild (1975) do not appear to be consistent with the polarization data. Schwarzschild's (1975) analysis was based on scaling the sizes of solar granules and supergranules to late-type supergiants. Any attempt to model the polarization observations in terms of solar features should consider the relevancy of the solar super-supergranulation (or giant) cells which have been suggested by Simon and Weiss (1968) and Bumba (1970). But it should be noted that the very existence of these large-scale solar features is a rather controversial topic (cf. Beckers and Canfield 1976).

The results of this survey may be summarized as follows. Betelgeuse has been intensively monitored over the nearly eight-month interval which comprised the 1980–81 observing season. The ordered polarization changes being reported here, and those of the tandem 1979–80 observing season, can be explained by the waxing and waning, and motion of large-scale elements of this star's lower atmosphere. Perhaps the most important data being reported here are the ordered polarization position angle changes. These changes are attributed to changes in the orientation of the element. While the observations have been shown to be inconsistent with a single global nonradial pulsation mode, they are not inconsistent with local modes. Such local nonradial pulsation modes are favored to explain the polarization variations being reported here.

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