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PERIODIC PHOTOSPHERIC AND CHROMOSPHERIC MODULATION IN ALPHA ORIONIS (BETELGEUSE)

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ABSTRACT

The bright cool supergiant Alpha Orionis (Betelgeuse; M2 Iab) has been monitored spectroscopically and photometrically over the past three years (1984–1986) in the optical and the ultraviolet wavelength regions. A 420 day periodic modulation of the flux is observed in the optical ($\lambda 4530$) and ultraviolet ($\lambda 3000$) continua, and in the Mg II ($\lambda 2795$ and $\lambda 2802$) line emission cores. Periodic photospheric pulsations are the most likely explanation of these observations. This identification is based on the large amplitude of the variation, the correlation of the continuum and chromospheric fluxes, and the length of the observed period. Pulsation may heat and extend the atmosphere of Alpha Ori and initiate the mass flow from the star.

Subject headings: stars: individual (Alpha Orionis) — stars: pulsation — stars: supergiants — ultraviolet: spectra

I. INTRODUCTION

Alpha Ori was one of the early targets of photometrists and spectroscopists more than half a century ago. This supergiant appeared to have a light and velocity modulation with a 5.78 yr period, on which were superposed irregular fluctuations with 100–200 day time scales (see Goldberg 1984; Guinan 1984). Detailed studies revealed periodic variabilities. Cycles of varying length (200–400 days) were first identified in AAVSO visual observations (Stothers and Leung 1971); Mg II line ratios exhibited a 1.1 yr period (Sonneborn *et al.* 1986); five periods ranging from 1.05 to 20.5 yr emerged from analysis (Karovska 1984, 1987) of 60 yr of AAVSO visual magnitude estimates.

The star is losing mass rapidly ($\sim 10^{-6}\ M_\odot\ \mathrm{yr}^{-1}$) and is surrounded by an extensive circumstellar envelope. The mechanism responsible for atmospheric extension and mass loss is still obscure. Alfvén-wave–driven wind models tend to accelerate the gas too rapidly near the star (Hartmann and Avrett 1984). While radiation pressure on dust grains is a very plausible mechanism to drive mass loss at large distances from the photosphere (Knapp 1986), the grains may not form close enough to the photosphere to initiate the flow (Draine 1981).

A program was established in 1984 at the Center for Astrophysics to monitor Alpha Ori at the Mount Wilson Observatory, and the Villanova Observatory, and by using the *International Ultraviolet Explorer* (*IUE*) satellite. Early results indicated variability (Dupree *et al.* 1984, 1986*a*) and a 1.1 yr periodicity in the Mg II line ratios (Sonneborn *et al.* 1986), but only recently has the full extent of its periodic behavior been discovered. These continuous, dedicated observations for the past 3 yr have revealed a fundamental *periodic* process in Alpha Ori, that is most probably pulsation. A brief summary was reported earlier (Dupree *et al.* 1986*b*; Dupree 1986). These results are of particular interest since pulsation may be a process critical to heating and extending a low gravity stellar atmosphere, and perhaps initiating a mass flow.

II. OBSERVATIONAL MATERIAL

Visible photometry.—The 38 cm reflector at Villanova University was used[5] with an intermediate-band (200 Å) blue filter centered at $\lambda 4530$ (denoted as the "*B*" band), and a neutral density filter (Guinan *et al.* 1982) in order to carry out differential photoelectric photometry between Alpha Ori and nearby comparison and check stars. These measurements were transformed to approximate the *B* band by comparison with other contemporaneous *B* magnitudes (Krisciunas 1982*a*, *b*). The photometric observations are shown in the top panel of Figure 1.

Ultraviolet photometry.—Long-wavelength low-dispersion spectra were obtained through the large aperture with the LWP camera of the *IUE*. Thirty-five spectra were obtained over the time interval 1984.02–1986.90 with exposure times of 4.6–5 s. The spectra were calibrated using the results of Cassatella and Harris (1983) and the flux extracted over a 100 Å interval ($\lambda\lambda$ 2950–3050). Recent studies (Sonneborn and Garhart 1986) show that the sensitivity of the LWP camera changed by less than 1% per year through 1986.4 and that the reproducibility of an individual observation over a 150 Å

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[5] S. W. Wacker of Villanova kindly obtained most of the observations.

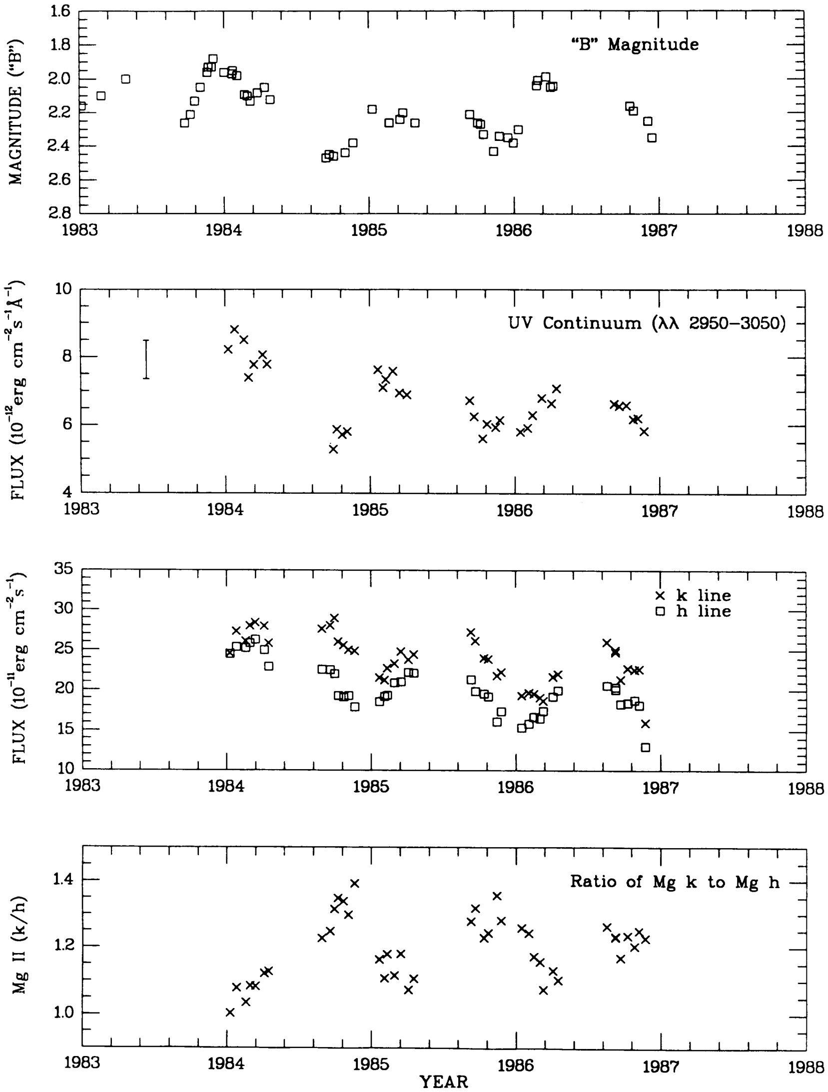

FIG. 1.—Observations of Alpha Ori 1983–1987.0. "*B*" magnitude denotes continuum flux at λ4530; Mg II *k* line (λ2795) and Mg II *h* (λ2802) line are shown in bottom panels.

interval is ~ 3.5%. A conservative estimate of ±6% is taken to be the error ($\pm 2\sigma$) of the flux measurement shown in the second panel of Figure 1.

Ultraviolet spectroscopy.—High-dispersion spectra (2.25 minute exposures) taken through the large aperture with the LWP camera of *IUE* were reduced and the fluxes of each member of the Mg II doublet were measured by summing the signal across the base of the emission core. The flux calibration factor between the high- and low-dispersion mode was taken as 100. Fluxes of the individual lines and the line ratio Mg II (*k*)/Mg II (*h*) are shown in the bottom panels of Figure 1. High-dispersion LWP spectra were taken also through the small aperture and analyzed for radial velocity variations (see below).

III. ANALYSIS

A period analysis was carried out following the techniques of Scargle (1982) and Horne and Baliunas (1986) after first removing linear trends from the data. A long-term modulation obviously exists that decreases the flux levels from 1984 through 1986. Corrected data sets and their Fourier transforms are shown in Figure 2 for the "*B*" magnitude, the UV continuum, and the Mg *h* line. A clear period of 1.15 yr (~ 420 days) appears both in the observed data directly, and as indicated by peaks in the Fourier transform of the data.[6] The derived periods for all of the data sets and the amplitude of variation are summarized in Table 1.

The Mg *h* and *k* line fluxes do not vary in a similar fashion (see the bottom panels in Fig. 1). This unexpected behavior may signal the presence of contamination by circumstellar or interstellar lines (Mn I, Fe I, Mg II) that affect the line profiles in the Mg doublet differently; either the

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[6] The Mg *k* line varies in anomalous fashion (see discussion below) and so is not given high weight in the period determination although it clearly partakes in the general atmospheric behavior.

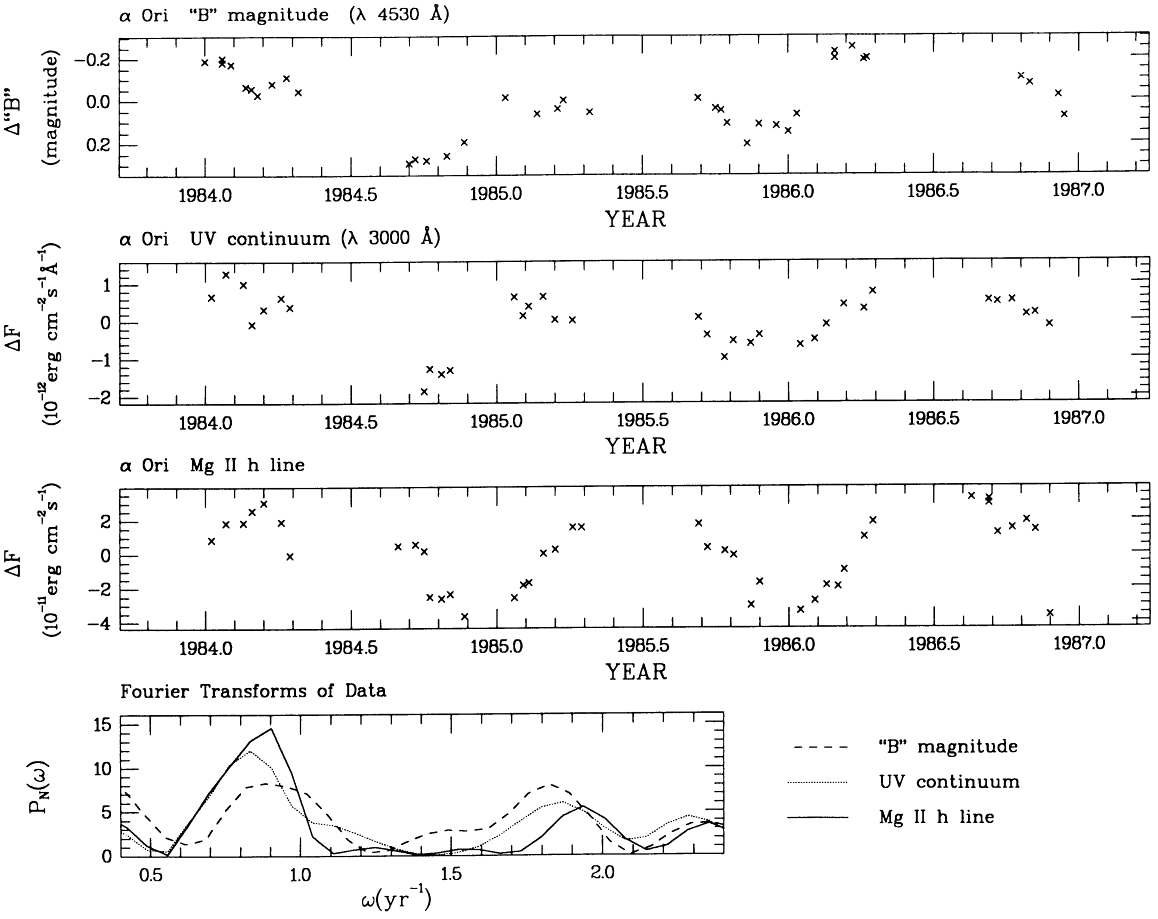

FIG. 2.—Observations of Alpha Ori 1984.0–1987.0 with linear dependence removed (*top three panels*) and the power spectra (*bottom panel*) of the three quantities: "*B*" magnitude; UV continuum; Mg II *h* (λ2802) line. A period of 420 days corresponds to ω (yr^{-1}) = 0.87.

TABLE 1

RESULTS OF PERIOD ANALYSIS: 1984.0–1987.0

Data	Period (yr)	False Alarm Probability[a]	Amplitude[b]
"*B*" magnitude	1.15 ± 0.05	0.92 %	0.13[c]
UV continuum			
(λ3000)	1.21 ± 0.03	0.023	0.83[d]
Mg II *h* (λ2802) ...	1.12 ± 0.02	0.002	2.89[e]
Mg II *k* (λ2795) ...	1.05 ± 0.02	0.02	3.25[e]
Mg II *k/h*	1.12 ± 0.02	0.001	0.106

[a] Probability that a false signal is detected in the definition of Horne and Baliunas 1986; expression in percentage.

[b] Semi-amplitude of variation of sine curve fitted to observations.

[c] Units: magnitude.

[d] Units: 10^{-12} ergs cm^{-2} s^{-1} Å^{-1}.

[e] Units of 10^{-11} ergs cm^{-2} s^{-1}.

strength of the circumstellar component varies or motions of the chromosphere relative to the circumstellar absorption features modify the appearance of the Mg lines. A changing wind opacity in Alpha Ori could also change the short wavelength side of each line (Dupree *et al.* 1986*a*). The flux in the Mg II *h* line (λ2802) follows the ultraviolet continuum variations better than the Mg II *k* (λ2795) transition.

IV. SOURCE OF PERIODICITY

Periodic variability in Alpha Ori could result from several possible causes: rotation of the star with surface features producing the light modulation, periodic emergence of large convective elements, some phenomenon associated with a companion star, or pulsation of the star causing compression and rarefaction of the atmospheric layers so that the temperature, densities, radiative losses, and velocities are modulated in approximately periodic fashion.

If rotation of a star with an inhomogeneous atmosphere produced the observed modulation, these surface inhomogeneities differ from starspots that have been identified on magnetically active stars. There, diminution of continuum light, caused by the presence of (dark) spots coincides with enhancement of chromospheric features (cf. Baliunas and Dupree 1982; Marstad *et al.* 1982). The behavior of Alpha Ori suggests that continuum brightenings and chromospheric losses are generally correlated. In addition to this discrepancy, the flux modulation observed in Alpha Ori (equaling a factor of 2 in the Mg II lines and continuum) greatly exceeds that found in other low gravity stars. For example, Lambda And (G8 III–IV), an active RS CVn binary, exhibits no more than a 20% variation in both the visible light and the Mg II flux between active and quiet phases (Baliunas and Dupree 1982).

Supergiants and bright giants hotter than Alpha Ori show an average of ±14% variability about the mean value in the Mg II *k* flux (Brosius, Mullan, and Stencel 1985).

If the observed periodic behavior were the result of rotation, then the equatorial velocity, $v(\text{eq}) \approx 60$ km s^{-1} for $R = 500\ R_\odot$. Such rapid rotation is unknown among M supergiants. Using the observed line widths of 13.5 km s^{-1} (Imhoff 1977) as an upper limit to $v \sin i$, one derives $\sin i \leq 0.2$. At this low inclination, it would be very difficult for rotational modulation by star spots to provide such a large Mg II variation.

Schwarzschild (1975) suggested that irregular variation in red supergiants could result from the appearance of a few hot convective elements on the surface of a supergiant with a temperature differential between hot rising elements and cool falling elements of ~ 1000 K. The regularity of Alpha Ori's behavior over the past 3 yr seems to argue against the erratic variability associated with the emergence of convective cells. Moreover, the temperature variation from observation of TiO bands has been estimated (Gaustad 1986) to be less than 100 K during 1984–1985 when the *B* magnitude changed by ~ 0.3 mag.

A suggested close-in companion star to Alpha Ori (Karovska, Nisenson, and Noyes 1986), might lead to atmospheric phenomena with a period commensurate with the 2.1 yr orbital period of the companion. However, this detection is controversial (Hebden *et al.* 1986).

Pulsation seems a more attractive explanation of the observed periodic variation since the chromospheric emission correlates well with the continuum behavior as in other well-known pulsating stars. Mg II emission in Cepheids appears suddenly, rapidly increases to a maximum (by a factor of ~ 3) during rising visible light, and then decays slowly (Schmidt and Parsons 1984). R Leo, a Mira variable, shows a large increase in its Mg II flux (by two orders of magnitude) that lags the maximum of the visual brightness by ~ 0.7 period (Brugel, Willson, and Cadmus 1986). This lag most probably results from the extended atmosphere of the Mira variable and the separation of the Mg II region from the photosphere during its postshock cooling phase. Alpha Ori shows a similar sequential pattern in its variability. Scattered Mg II observations from 1978 to 1984 hinted at a long-term pulsation process (Dupree *et al.* 1984). Close inspection of the variability in "*B*" magnitude and the ultraviolet continuum reveals minima approximately at 1984.75 and 1985.85; minima in the chromospheric Mg II *h* line flux, however, occur later, at ~ 1985.0 and 1986.0. (Maxima are not easily identifiable because of the seasonal gaps in observations, although observations near the 1984.0 maximum are not inconsistent with a lag of 0.2 yr in the Mg II maximum.) A lag in chromospheric variation after photospheric variations suggests that a propagating wave is present in the Alpha Ori atmosphere.

If the observed periodic modulation of the *B* magnitude results only from the changing size of the star, a radius change of ~ 15% is required. Such a change can be accommodated within the existing direct measures of the diameter of the star (White 1980; Karovska 1987) although a fixed stellar radius is frequently assumed in conjunction with wavelength dependent limb-darkening, a circumstellar envelope, and possible circumstellar features (Cheng *et al.* 1986) in order to interpret speckle interferometry measures.

Velocity variations would be expected and the photosphere of α Ori does appear to vary in velocity (Sanford 1933; Boesgaard 1979; Goldberg 1984), although the small amplitude (~ 5 km s^{-1}) and large broadening of emission lines make optical measurements difficult. We attempted to search for radial velocity variations by cross-correlating selected high-resolution LWP orders of spectra taken through the small aperture. Photospheric absorption lines and Fe II emission lines show no changes in velocity in 24 measurements over 2 yr (1984.6–1986.8) with a dispersion of ±3 km s^{-1}, consistent with our expected error of measurement. Cross-correlations of high-resolution optical spectra in the Hα region also reveal no velocity variations above a level of ±3 km s^{-1} during 1984.5–1985.5. However, the velocity difference between Ca I (λ6573) and the Hα core did show an expansion and contraction with an amplitude of about 5 km s^{-1} over a time scale of 150–200 days with a maximum difference near 1984.86 (Dupree *et al.* 1986*a*). The sequential nature of the photometric minimum (~ 1984.7), the Hα core event (~ 1984.8), and the Mg II minimum (~ 1985.0) may result from an outwardly propagating disturbance.

Calculations (Stothers and Leung 1971; Lovy *et al.* 1984) of the pulsational modes in low-gravity cool stars suggest that the fundamental mode of pulsation is approximately 400 days for a star with $T_{\text{eff}} = 3400$ K and $L \approx 5 \times 10^4\ L_\odot$. Moreover, for radial pulsation the quantity $(A_{\text{RV}}/A_V)(P/R_0)$ for cool stars turns out to be approximately 2–4 (Balona and Stobie 1979; Lovy *et al.* 1984). Here *A* denotes the amplitude in radial velocity and visual magnitude, *P*(days) is the pulsation period, and R_0 ($R_\odot$) is the equilibrium radius. Inserting quantities for α Ori ($A_V = 0.4$ m;[7] $R_0 = 500\ R_\odot$; $P = 420$ days), we predict the radial velocity amplitude of the fundamental mode to be 1–2 km s^{-1}, a value consistent with our upper limit. It would be extremely important to obtain velocity measures of α Ori with high precision in order to detect such a variation.

The period of pulsation may not be constant with time. This may explain, in part, the difference between our period determination and one of Karovska's (1987) five periods derived from visual magnitude estimates obtained over 60 yr; additionally, our photoelectric magnitudes are more precise. A pulsation period of 420 days places Alpha Ori in agreement with other evolved stars with respect to the energetics of its stellar wind (see Fig. 10 of Knapp 1986) and also with the locus defined by supergiant OH/IR sources in a period-luminosity relation (see Fig. 3 of Jones *et al.* 1983).

Periodic pulsations that become shocks traveling through the outer atmosphere of Alpha Ori could be responsible for heating and extending the inner circumstellar envelope. The observed modulation of the Mg II lines supports chromospheric heating by the effects of pulsation. The damping length of these waves could be ~ sound speed × period ≈ 7 km s^{-1} × 1.15 yr ≈ 0.7 R_*, consistent with the conclusion of Hartmann and Avrett (1984) that the extended chromosphere is heated by waves with damping lengths ≈ 1 R_*. The damping of such pulsational shock waves could significantly extend the inner atmosphere and help to initiate mass outflow.

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[7] Estimated from Fig. 2 for *B* magnitude, since there is no significant wavelength dependence in variation of *B*, *V*, and *R* (Guinan 1984).

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