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THE MAGNETIC FIELD OF SIGMA ORIONIS E

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ABSTRACT

We have detected a magnetic field in the peculiar variable helium-rich B2 star σ Ori E. The field varies between -2300 and $+3100$ gauss with the $1^d.19$ period of the spectroscopic and light variations of the star. We suggest that the detection of this field allows all the variable phenomena of σ Ori E to be understood in terms of an oblique rotator model that has hot gas trapped in a magnetosphere above the magnetic equator, and atmospheric helium enhancement which has occurred preferentially in a zone around the magnetic equator.

Subject headings: stars: circumstellar shells — stars: emission-line — stars: individual — stars: magnetic — stars: spectrum variables

I. INTRODUCTION

The star σ Ori E is a member of a Trapezium-like system in the Orion aggregate which contains at least five stars. It has the effective temperature, surface gravity, and absolute magnitude appropriate to a B2 V star, but it shows abnormally strong lines of helium and appears to have $X \approx 0.3$, $Y \approx 0.7$ in the atmosphere (Greenstein and Wallerstein 1958; Klinglesmith *et al.* 1970; Lester 1972). It is the prototype of a small class of helium-rich stars discussed by Osmer and Peterson (1974). These stars have spectral types close to B2 V, lie on the main sequence, and have overabundances of helium, oxygen, and nitrogen of roughly an order of magnitude. Osmer and Peterson suggest that these stars may be an extension to higher temperature of the Bp phenomenon. The helium-rich stars are in a region of the H-R diagram in which radiatively driven mass loss is believed to occur, and Vauclair (1975) has suggested that the helium overabundance may be due to a combination of general outward mass flow together with a relative inward diffusion of helium, which under suitable circumstances may cause helium to accumulate in the stellar atmosphere.

Many features of σ Ori E have been found to vary with time. The strength of the photospheric helium lines varies (Hunger 1974; Thomsen 1974), and variable Hα emission with a total width of up to ~40 Å was found by Walborn (1974). Bolton (1974) showed that radial-velocity variations are less than about 4 km s^{-1}, so that if a companion is present, and the emission is due to an accretion disk of some kind in the system, the companion must have quite low mass or the binary orbit must be nearly in the plane of the sky.

Walborn and Hesser (1976) found that light variations occur with a period of $1^d.19$, one of three periods previously found by Thomsen (1974) for helium line variations. Hesser, Walborn, and Ugarte (1976) subsequently found that two eclipse-like drops in brightness occur each cycle. The Hα emission varies on this period as well. Groote and Hunger (1976, 1977) discovered a variable shell spectrum in the higher Balmer lines which appears only during the eclipses; they found that, although the radial velocities of the photospheric H and He lines remain constant, the shell lines vary by up to ± 60 km s^{-1}, negative going into eclipse and positive coming out. Finally, Kemp and Herman (1977) find a small variable component of linear polarization for σ Ori E, again varying in the $1^d.19$ period.

The nature of σ Ori E has been discussed in terms of an oblique rotator model, which is suggested by the helium spectrum variations, and in terms of a binary system with an accretion disk, suggested by the eclipses and the Hα emission (Thomsen 1974; Walborn and Hesser 1976; Hesser, Walborn, and Ugarte 1976; Groote and Hunger 1977; Kemp and Herman 1977). No clear consensus has emerged about an appropriate model for this peculiar star.

In this *Letter* we report the discovery of a magnetic field in σ Ori E, and discuss a model of the star which is suggested by this discovery.

II. OBSERVATIONS

Magnetic observations of σ Ori E were obtained by using a photoelectric Pockels cell Balmer-line Zeeman analyzer on the 1.5 m telescope of Palomar Observatory. This instrument and our data acquisition and reduction procedures are described by Borra and Landstreet (1977) and Landstreet and Borra (1977). Because σ Ori E has a large value of $v \sin i$, about 150 km s^{-1} (Klinglesmith *et al.*), this technique is at present the only practical method of detecting a field in the star. A field of almost 3000 gauss was detected during the first magnetic observation of σ Ori E, and the star was subsequently observed for seven consecutive nights, which gives coverage right through the 1ᵈ19 period. The profile of Hβ, which is the line used in these observations, was obtained on three nights. We found the line to be essentially constant in profile. Using the mean profile, the relationship between measured polarization and effective field strength is found to be B_e(gauss) = 19000 V(%). Our observations are listed in Table 1, and shown in Figure 1. Phase is computed from the ephemeris of the light curve, JD (primary minimum) = 2,442,778.819 + 1.19080E (Hesser *et al.*). The field clearly varies with the same period as the other variables. Because of the high precision of the current period, the relative phase of the magnetic observations and other reported variations is uncertain by only ~0.02 cycle.

TABLE 1

MAGNETIC OBSERVATIONS OF σ ORI E

JD (2,440,000+)	ϕ	$B_e \pm \sigma_B$ (gauss)
3441.904	0.840	+2820±460
3442.921	0.694	+2620±460
3443.915	0.529	+1400±470
3444.925	0.377	− 970±470
3445.868	0.169	−2170±470
3446.931	0.061	−1680±470
3447.801	0.792	+2480±470
3447.997	0.957	+1310±410

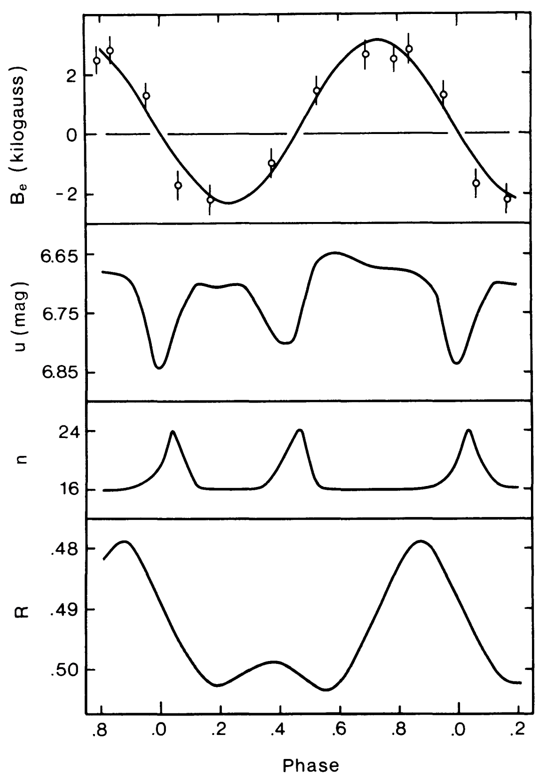

FIG. 1.—Observed variation of σ Ori E as a function of phase. *Top to bottom:* longitudinal magnetic field strength B_e (error bars are ±1 σ_B, and the smooth curve is the best-fit sine wave); Strömgren u magnitude; number n of the last visible Balmer line; and variation in the photoelectric line strength index R which measures the strength of He I λ4026 (small R corresponds to large equivalent width). The lowest three smooth curves are hand-drawn fits to the data.

The magnetic curve appears roughly sinusoidal in shape. The best-fitting sine wave is shown in Figure 1 as a smooth curve; it is a curve of the form $B_e = B_0 + B_1 \sin 2\pi\ (\phi - \phi_0)$, where $B_0 = +400 \pm 300$, $B_1 = 2700 \pm 500$, and $\phi_0 = 0.48 \pm 0.03$. The value of χ^2 for the best fit is 6.8. (The uncertainties of the parameters of the curve have been set by the requirement that χ^2 not exceed 11.1, the upper limit of χ^2 at 95% confidence for 5 degrees of freedom.)

The field variations observed may clearly be fitted by a centered oblique dipole rotator model, and it is of interest to try to estimate the parameters i (inclination between the rotation axis and the line of sight), β (inclination between the magnetic and rotation axes), and B_p (polar field strength). Because σ Ori E is a physical member of a system containing a substantially more massive star, it is probably nearly on the zero-age main sequence; for the temperature derived by Klinglesmith *et al.*, this gives $R = 3.5\ R_\odot$. Then from $\sin i = P\ v \sin i/(50.6\ R)$ we find a most probable value of i of about 90°, so we see the star more or less from its (rotational) equatorial plane. Unfortunately, this leaves β almost unconstrained. For $\beta \sim 90°$, B_p is about 10,000 gauss. This value is a lower limit.

III. DISCUSSION

Figure 1 illustrates the phase relationship between the magnetic variations and other variable features of σ Ori E. Successive panels of the figure show the effective field variation, light variations in the Strömgren u band (Hesser *et al.*), the number n of the last visible Balmer shell line (Groote and Hunger 1977), and the variation in a photoelectric index R which measures the strength of He I λ4026 (Pedersen and Thomsen 1977). As may be seen in the figure, the eclipses and shell episodes coincide closely with $B_e = 0$ on the magnetic curve. Thus the eclipses and the appearances of shell lines occur when the line of sight to σ Ori E lies in the plane of the magnetic equator of the star.

The fact that shell lines appear only when the line of sight is nearly in the plane of the magnetic equator implies that the circumstellar gas responsible for these lines is localized in the region above the stellar magnetic equator. It is natural to consider the possibility that the magnetic field is responsible for this effect. If gas is driven out of the photosphere in some way, for example by radiation pressure, it would presumably be able to leave the star fairly freely along open polar field lines, but could be trapped, or at least greatly slowed down, in the region of closed field lines above the magnetic equator, where its density might rise to considerably greater values than over the poles. The denser gas above the magnetic equator could then produce the shell line episodes, and perhaps also contribute to the eclipse-like light variations.

This picture gives a natural explanation for the observed synchronism of photospheric phenomena (helium line and magnetic variations) and circumstellar ones (appearance of shell lines and variations in Hα emission strength), and also predicts that two shell phases and eclipses should occur per rotation of the star, since the line of sight crosses the magnetic equator twice per rotation.

We may easily estimate the extent of the magnetically dominated region. The magnetic field B_s at the stellar surface is $\sim 10^4$ gauss. For the outflowing gas to be restrained by the magnetic field, the energy density of the field at height r above the stellar surface [$\epsilon_B = B^2/8\pi \sim B_s^2\ (R^3/r^3)^2/8\pi$] must exceed the kinetic energy density of gas which is forced to corotate [$\epsilon_R \sim nm_H v^2/2 \sim nm_H(2\pi r/P)^2/2$]. The boundary of the magnetosphere will occur at a height r_m where $\epsilon_k \sim \epsilon_B$; with $n \sim 10^{12}$ cm^{-3} (see below), this gives $r_m/R \sim (16\pi^3 nm_H)^{-1/8} (B_s P/R)^{1/4} \sim 2.8$. Equatorial field lines which rise to a height of less than r_m will presumably remain closed and trap or at least impede outflowing gas, forcing it to corotate with the star; polar field lines which extend beyond r_m will be open and gas will flow out relatively easily along them.

We next assess the conditions in the circumstellar gas, and consider whether it may be related to the light variations. The gas might contribute to the light variations either as an emitting volume which is eclipsed by the star, or as an absorbing and/or scattering cloud which at some phases reduces the light arriving from the stellar photosphere.

From the number of the last Balmer line observed during the shell phases, we infer $n_e \sim 2 \times 10^{12}$ cm^{-3} in the circumstellar material from the Inglis-Teller formula (Allen 1973). At such low densities the gas near the star should be essentially all ionized even at $T \sim 10^4$ K, so $n_p \approx n_e$. If we assume that the gas is optically thin in Hα, we may use Tables 4.4 and 4.7 of Osterbrock (1974) to estimate the ratio of the flux in Hα to the ultraviolet continuum flux radiated by the circumstellar gas clouds due to recombination and brehmsstrahlung. We use the facts that the Hα emission is observed to rise to at most about 10% above the stellar continuum and that it has a full width of about 40 Å to superpose the flux spectrum of the gas on the continuum spectrum of a B0 star (Allen 1973, § 99). It is found that the emission from the gas is about 10^{-3} of the stellar continuum just shortward of the Balmer jump, and an order of magnitude less around 4000 Å. Thus emission from the gas does not contribute significantly to the continuum radiation from the star in the photometric bands in which an eclipse is observed.

Again using the observed ratio of the Hα line strength to stellar continuum, we may estimate the emitting volume, assuming that the gas is optically thin in Hα; a typical dimension is $D \sim 10^{11}$ cm, about the size of the star itself, which is consistent with the model we have developed here.

Next, consider the effects of the circumstellar gas as a scattering and absorbing medium. The optical depth in electron scattering τ_{sc} may be estimated if we assume that the dimension 10^{11} cm derived above applies to the depth of the circumstellar gas region along the line of sight; in this case $\tau_{sc} \sim 10^{-1}$, with an uncertainty of perhaps a factor of 10 either way.

Absorption comes from both free-free and bound-free transitions. Because of the low density, the free-free absorption coefficient is about a factor of 10^2 less than the electron scattering coefficient, and free-free absorption is not important. The importance of bound-free absorption is more difficult to assess, as this process depends on the number of neutral atoms in the $n = 2$ or 3 state. If we estimate these populations using the Saha and Boltzmann equations with $T = 10^4$ K, we find that the optical depth due to bound-free absorptions is comparable to that due to electron scattering in the Balmer continuum and an order of magnitude smaller in the blue Paschen continuum.

It should also be possible to estimate the strength of Balmer continuum absorption from the observed strengths of the Balmer shell lines, which arise from the same lower level. Unfortunately, the spectrophotometry of σ Ori E during the shell phase published by Groote and Hunger (1976) gives only photographic density, not intensity, so true line depths are hard to estimate. Furthermore, the ratio of line to continuum absorption depends on the velocity field in the gas. The shell absorption lines are about 2 Å wide (about 10 times the thermal width for hydrogen at 10^4 K). If this is a microturbulent velocity dispersion, the Balmer continuum absorption near the edge should be comparable to the line absorption in H20 to H25, so the continuum optical depth is at least $\sim 10^{-1}$.

Thus it is quite possible that the gas above the magnetic equator may be at least partly responsible for the eclipses by acting as scattering or absorbing screen each time it passes in front of the star. This gas may also cause the small double wave of intrinsic linear polarization seen in B filter observations made by Kemp and Herman (1977), which is maximum at the two phases when the gas clouds (or ring) are in the plane of the sky. (It is not clear how to interpret the single wave variation of polarization observed in the U filter, which is maximum near an eclipse phase.)

We next consider the helium line strength variations observed for σ Ori E. On an oblique rotator model of the star we would expect helium lines to show radial-velocity variations. These are not observed. Groote and Hunger (1977) report that the observed equivalent-width variations may be reproduced adequately with a two-spot model, but radial-velocity variation of ± 30 km s^{-1} is then predicted, far greater than the ± 2 km s^{-1} upper limits. Shore (1977) has recently tried distributing the helium in a ring around the star, a distribution probably more in keeping with the magnetic geometry, since both He line strength maxima occur near passage of the magnetic equator over the subsolar point, but with this distribution a radial-velocity problem also arises.

We suggest that the discrepancy between the radial-velocity variation predicted by the oblique rotator model and the lack of observed radial-velocity variation may occur because of the procedure by which the radial velocities are measured. The atmosphere of σ Ori E is at a temperature at which helium lines are near maximum strength, and is probably everywhere excessively rich, or at least normal, in helium, so that the helium lines which are measured for radial-velocity variation are fairly strong. Such lines typically consist of a rather boxy, saturated core plus broad, shallow damping wings. Under these conditions, abundance variations may have relatively little effect on the line cores, but primarily affect the damping wings. Thus, if a helium-enriched region of the atmosphere is coming into view while a region with lower (but still anomalously high) helium abundance is receding toward the opposite limb, both regions may contribute similar line cores to the integrated line profile, but the damping wings of the approaching helium-rich area will be stronger than those in the receding, less enriched area. Thus the core of the line should show a fairly small radial-velocity variation; most of the variation will occur in the damping wings. But the observer measuring radial velocities weights the core much more heavily than the wings, both when measuring visually on a Grant comparator (Bolton 1974) and when comparing profiles numerically by using the correlation function preferred by Groote and Hunger (1977). Thus we propose that radial-velocity variations in fact occur in the helium lines of σ Ori E, but in such a way as to largely escape detection.

We next consider the relationship between the magnetic field and the distribution of photospheric material. It appears that the helium is most strongly anomalous (enhanced) in a ring running roughly around the magnetic equator, as discussed by Shore (1977) (or perhaps at two spots where magnetic and rotational equators cross). This is an unusual situation for Ap stars, where abundance anomalies typically concentrate at magnetic poles, but may be found in at least one other star, CU Vir = HD 124224, the most rapidly rotating classical Ap star known (Landstreet and Borra 1977; details of this model have been disputed by Molnar and Wu 1978). If Vauclair's (1975) model for helium over-abundance (see § I) is applicable to a magnetic star such as σ Ori E, it appears that mass outflow at the magnetic poles of the star is too large for strong atmospheric helium abundance anomalies to occur, while a more moderate outflow occurs near the magnetic equator, allowing a helium-rich photosphere to form.

Shore (1977) has suggested that the eclipse-like light variations may be similar in nature to the light variations produced in Ap stars by variations in blanketing and back warming over the stellar surface caused by the photospheric abundance variations; he reports that preliminary calculations of this effect with helium over-abundant in a ring running roughly around the magnetic equator of the star seem quite similar to the observed light curve.

It thus appears that the phenomena found in σ Ori E may be interpreted in terms of an oblique magnetic rotator model with hydrogen trapped in the magnetosphere above the magnetic equator and atmospheric helium enhancement in a ring around the equator. It does not seem necessary to invoke a binary model with an accretion disk or ring. One point that does still need to be explained comprises the very large velocities found in the Hα emission, but this may be in some way related to mass flowing out through the magnetic pole region, and does not seem to be an essential obstacle to understanding this star as an oblique magnetic rotator.

Finally, we may remark that the detection of a field in σ Ori E confirms the conjecture of Osmer and Peterson that the helium-rich stars are a hotter extension of the Bp (helium-weak) stars.

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