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ON THE NATURE OF SIGMA ORIONIS E

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ABSTRACT

A period of 1ᵈ19 has been found in observations of the Hα emission intensity, He absorption-line strengths, magnitudes, and colors of the helium-rich star σ Ori E. The Hα emission variation is a double wave with two unequal maxima separated by about one-half the period. The primary Hα emission and He absorption maxima coincide. They are followed about one-quarter period later by a sharp continuum-flux minimum, the amplitude of which increases with decreasing wavelength. The radial velocities are uninformative. Some characteristics of the variations are reminiscent of the oblique rotator model, while others suggest the presence of a very low-mass companion.

Subject headings: stars: early-type — stars: eclipsing binaries — stars: hydrogen-deficient — stars: rotation — stars: spectrum variables

I. INTRODUCTION

The existence of a broad (1800 km s^{-1}), rapidly variable emission feature at Hα in the spectrum of the helium-rich star σ Orionis E was reported by Walborn (1974). However, no consistent pattern in the variations emerged, and the radial velocity was found to be constant to within ±4 km s^{-1} by Bolton (1974). Subsequently, the He absorption-line spectrum in σ Ori E was reported to be strongly variable by Hunger (1974), Thomsen (1974), and Nissen (1974). Thomsen found several possible periods, all of which yielded double-wave phase diagrams.

In order to obtain further information about the variations, σ Ori E was monitored at CTIO with three telescopes simultaneously during 1974 December 2–5 UT. As described below, these data have led to the discovery of a periodicity of 1ᵈ19 in several observationally independent parameters; this value is identical with equation (11) of Thomsen (1974), and now appears most likely to be the correct period.

II. NEW OBSERVATIONS

Spectrograms were obtained with the 90 cm telescope alternately at Hα and in the region λλ3800-4400; the dispersions were 84 and 42 Å mm^{-1}, respectively. The plates were calibrated by means of a spot sensitometer. At Hα, the heights of the violet and red sides of the emission relative to the continuum, and the central depth of the absorption, were determined on intensity tracings.[1] In the blue, equivalent widths of several H and He I lines were measured with a planimeter; central depths and full widths at half-maximum intensity were also determined. In addition, radial velocities were measured from the blue plates with the CTIO Grant machine.

The Hα profile of σ Ori E was monitored with the two-channel scanner at the 1.5 m telescope, with a 4 Å exit slot and 4 Å steps across the region λλ6512–6612. A complete scan, interchanging star and sky channels, required about 18 min. Each combined 40 s integration produced ∼0.6 percent photon statistics. In addition, continuum fluxes at 24 wavelengths between 3390 and 7850 Å were measured several times each night for σ Ori E and standard stars (Hayes 1970; Oke and Schild 1970).

Concurrent *uvby–β* observations were made by Sr. Patricio Ugarte P. with a 1P21 photometer at the No. 1 40 cm telescope. Between 10 and 20 standard stars were observed each night for determination of mean extinction coefficients and for transformation to the standard systems (Crawford and Mander 1966; Crawford and Barnes 1970). A measurement consisted of a series of 10 s integrations requiring about 6 min for completion. Typical rms errors in transformation were about 0.015 mag for all indices.

III. RESULTS

a) The Period

The photoelectric magnitude and color data were analyzed with a Lafler-Kinman (1965) period-search program, which suggested, among others, values near 0ᵈ58 and 1ᵈ19. When these values were applied to the Hα emission data of Walborn (1974), which are more extensive in time, a clear double-wave variation of period 1ᵈ19 was found (Fig. 1). These data are sufficient to show that the period is significantly nearer 1ᵈ19 than either 1ᵈ18 or 1ᵈ20.

One cannot eliminate *a priori* a single-wave period of 0ᵈ595. However, there are indications that the double-wave interpretation is correct; for instance, the $V + R$ secondary-maximum points of Figure 1 fall systemati-

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[1] In the previous paper (Walborn 1974) the Hα profile parameters were measured on density tracings and then converted to intensities. Due to an improper procedure in the case of the absorptions, the numbers given as "central depths" in Table 1 and Figure 3 of that paper were inadvertently the difference of the continuum and central absorption intensities divided by the *central absorption* intensity, instead of by the continuum intensity. Those numbers can be converted to proper central depths by a simple arithmetic procedure.

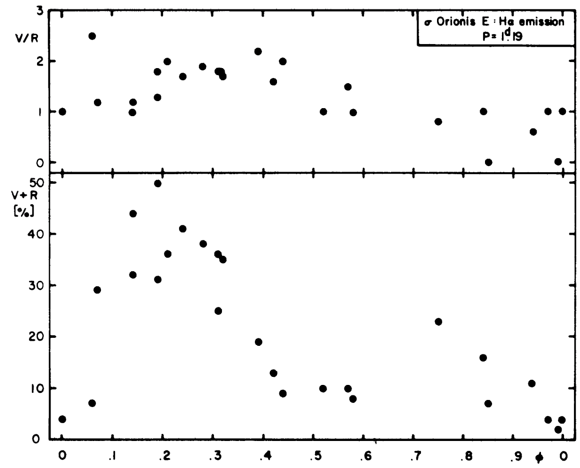

FIG. 1.—The Hα emission data of Walborn (1974), phased with a period of 1ᵈ19 relative to 1973 December 2.0 UT = JD 2,442,018.5. V and R are the percentage heights of the violet and red sides of the emission above the continuum, respectively.

cally low when the data are phased with the single-wave period, and the V/R values are systematically different near the two $V + R$ maxima in Figure 1. Also, 1ᵈ19 corresponds exactly to one of the best of Thomsen's (1974) double-wave periods from his photoelectric He I λ4471 absorption index. When one compares Thomsen's data with the Hα emission strengths in Figure 1, the primary maxima of both variables are seen to be essentially coincident. (The phases in his Fig. 3 and the present Fig. 1 are, fortuitously, virtually identical.)

b) The Blue Helium and Hydrogen Lines

The equivalent widths of Hδ and He I λ4026 together with Hα emission heights from the new spectrograms, phased with a period of 1ᵈ19, are illustrated in Figure 2. (There is an arbitrary phase shift with respect to Fig. 1). Significant systematic effects are seen in the He-line strength, with a maximum near the Hα emission maximum. Unfortunately, due to the crucial lack of new data between phases 0.3 and 0.6, a double-wave variation is not clear; however, it is considered most likely in view of the information discussed in § III*a*, above. The strength of Hδ itself, on the other hand, shows no systematic behavior, except that the scatter is more than twice as great in the vicinity of the Hα emission maximum.

The profiles of the blue He I and H lines undergo large variations. For instance, in spectrograms obtained consecutively at phases 0.92 and 0.94, He I λ4026, Hδ, and Hγ have deep, narrow cores, with full widths at half-maximum of 4–5 Å, about half the largest values observed. It is not clear at the present time whether or not this behavior is periodic.

c) The Radial Velocities

The radial-velocity phase diagram shows no systematic structure. The average velocity is 26.6 km s^{-1} with a mean error of the average of 2.8 km s^{-1}, in good agreement with Bolton (1974). The internal mean errors of the present plates range between 3 and 7 km s^{-1}, while the external mean error for a single plate is 10.6 km s^{-1}. Two low (~10 km s^{-1}) and two high (~40 km s^{-1}) values were obtained; they are not obviously related to any instrumental problems or the profile variations, and their origin remains a question.

d) The Scanner Hα *Profiles*

The phase behavior of the Hα profiles observed with the scanner is shown in Figure 3. After a line was drawn through the outermost points in the continuum region, the equivalent widths, W, of the Hα absorption and emission features were determined from the profiles by

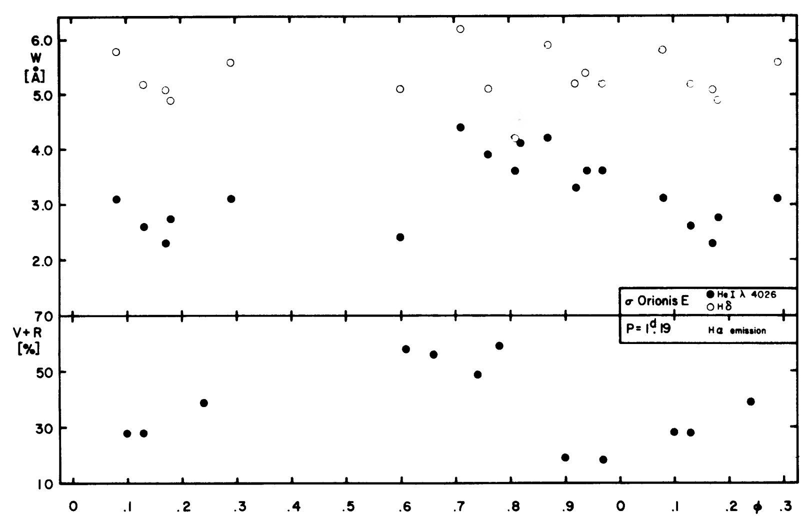

FIG. 2.—Equivalent widths of Hδ and He I λ4026 together with Hα emission heights, from the new data, phased with a period of 1ᵈ19. Here, as well as in all subsequent diagrams of this paper, phase zero corresponds to 1974 December 2.0 UT = JD 2,442,383.5.

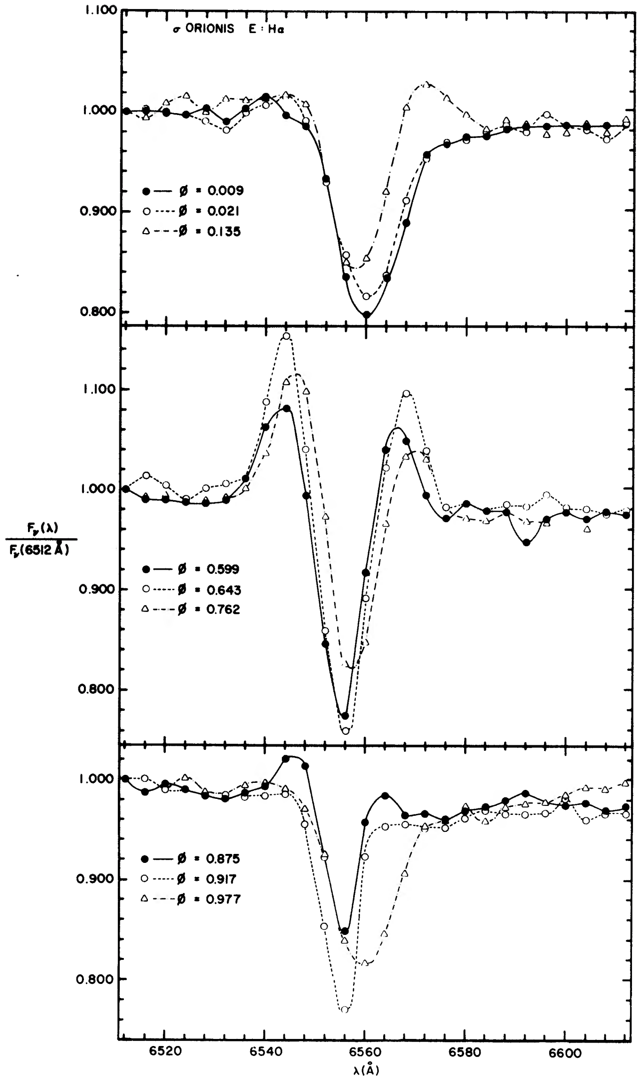

FIG. 3.—Normalized scanner Hα profiles corresponding to 9 phases in the 1ᵈ19 period. The wavelength scale may be uncertain by ~4 Å, the width of the exit slot used. From top to bottom, profiles for phases 0.009 and 0.021 are from 1974 December 3; for 0.135 from December 2; for 0.599–0.762 from December 5; for 0.875 and 0.917 from December 4; and for 0.977 from December 3. The connecting curves are hand-drawn.

planimetry. They are plotted for a period of 1ᵈ19, along with W_V/W_R and F_ν (6512 Å), the flux at the bluest point in the average continuum, in Figure 4. The extreme values of the Hα absorption occur somewhat later than the opposite extrema of the emission strengths. The violet side of the emission is relatively more pronounced at later phases, whereas the red side is more pronounced at earlier phases. (The appearance of W_R in absorption is probably due to C II λλ6578–6583.) From the behavior of W_V/W_R, it is apparent that the emission maximum at phase ~0.7 in the new observations corresponds to the primary $V + R$ maximum in Figure 1. In view of the absence of marked systematic variations at Hδ, discussed above, and at Hβ, discussed below, it is most likely that the strong trends in the Hα absorption are due to variable filling-in by the emission.

e) The Photometry

The phase diagram with period 1ᵈ19 for y, b, u, $u - b$, and β (Fig. 5) shows a clear minimum near $\phi = 0.975$, but phase coverage is inadequate to allow the double-wave nature suspected from the earlier spectral observations (§ IIIa) to be clearly discerned. The (normally) temperature-sensitive $u - b$ index becomes more positive at minimum light, while β is more nearly constant. The scanner continuum observations confirm that the light variations are significantly greater in the ultraviolet.

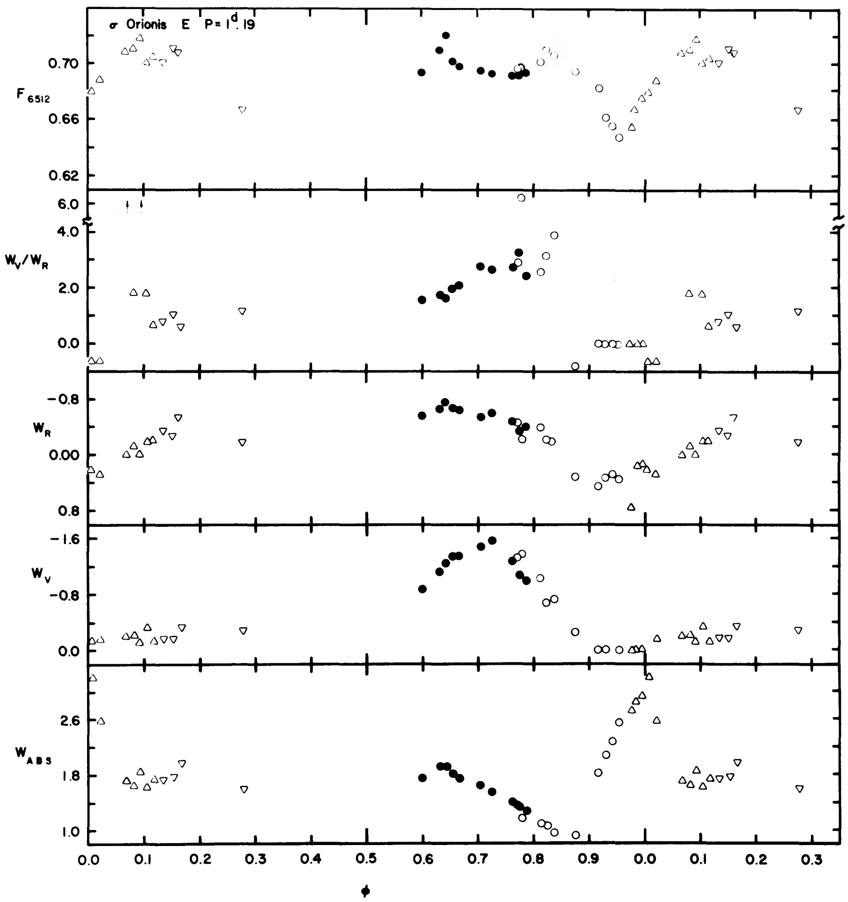

FIG. 4.—Phase diagrams for a period of 1ᵈ19 from an analysis of the scanner Hα profiles. From top to bottom are shown: the flux (in units of 10^{-22} ergs s^{-1} cm^{-2} Hz^{-1}) of the bluest point in the adopted continuum; the ratio of the equivalent widths of the violet (W_V) and red (W_R) sides of the emission feature; the individual equivalent widths, in angstroms, of the red and violet sides of the emission feature (negative implies emission); and the equivalent width, W_{abs}, of the absorption line. See text for discussion. Data from different dates are distinguished as follows: ∇, 1974 December 2; Δ, December 3; ○, December 4; and ●, December 5.

IV. DISCUSSION

The corresponding double-wave variations in the Hα emission and He absorption strengths of σ Ori E are suggestive of the oblique rotator model, as is the absence of strong systematic variations in Hβ, Hγ, and Hδ (Mihalas 1973 and references therein). If σ Ori E is an oblique rotator, a striking consequence is that the presumably circumstellar Hα-emitting gas must lie above the He-enhanced spots on the stellar surface, and be constrained to corotate with them. Perhaps the magnetic field would be capable of maintaining such a configuration. However, it appears unlikely that σ Ori E could be explained by redistribution of a normal, primordial surface He content, as was possible for 56 Ari and a Cen (Mihalas 1973). Even the smallest value of W(He I λ4144)/W(Hδ) observed here (0.29 for the point at phase 0.6 in Fig. 2) is larger than that found in normal stars (Walborn 1975); perhaps convection to the surface of newly synthesized helium from the stellar interior would have to be considered.

On the other hand, several features in the phase diagrams presented above seem difficult to understand in terms of the oblique-rotator model. (1) The Hα emission V/R variation is very systematic, with extreme values displaced in phase from those of the emission strength itself (Figs. 1, 3, and 4); these remarks apply also to the Hα absorption strength (Fig. 4). It is possible that these effects are caused by a combination of variations in the emission profile and velocity shifting relative to the absorption. (2) The sharp light minimum centered at phase 0.975 (Fig. 5), corresponding to redder colors, coincides with Hα emission and He absorption minima. In 56 Ari and a Cen, *maximum* light and *bluest* colors are found at He minimum. Moreover, this minimum in the light and color curves of σ Ori E seems rather more distinct (eclipse-like) than might be expected for a "non-spot" region in the oblique rotator interpretation. If σ Ori E has a companion, Bolton's (1974) upper limit to the radial-velocity variation implies that its mass must be less than about 0.1 $M_{\odot}$ for inclinations greater than 45°. (See also Norris and Baschek 1972.) It is interesting that the Hα profiles with emission strong as well as the V/R variations in σ Ori E are similar to the Balmer

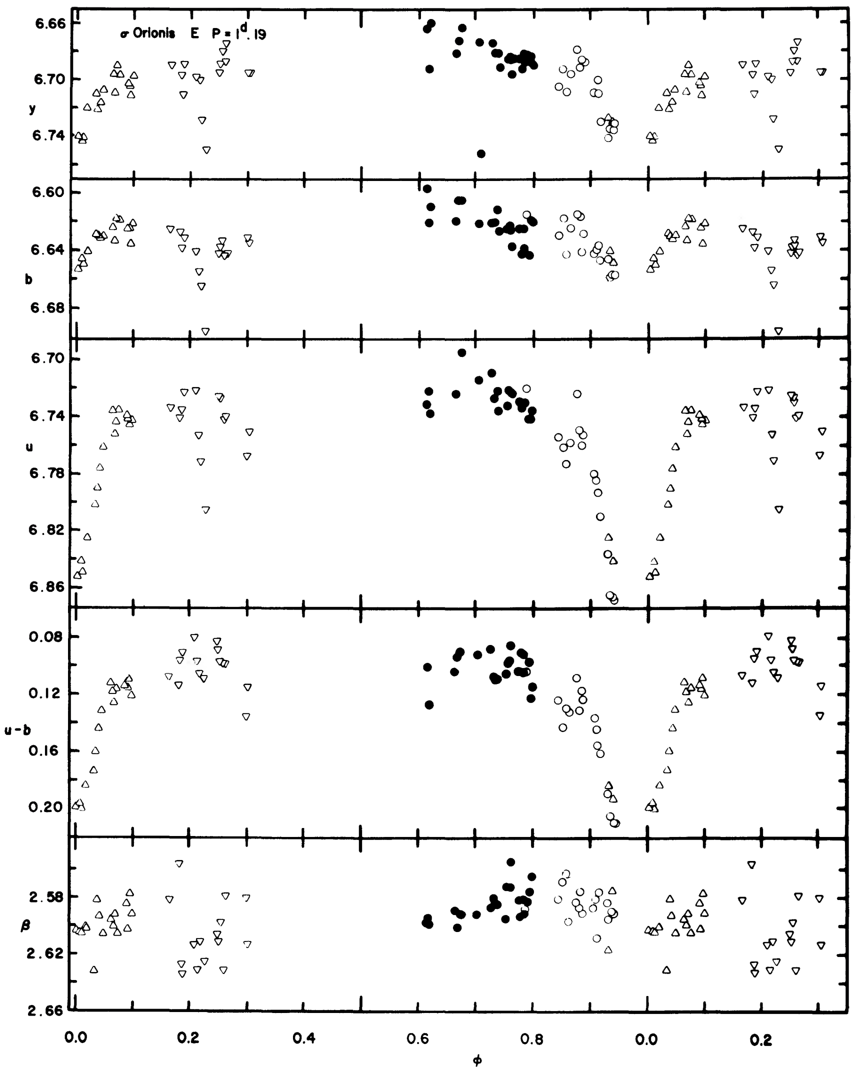

FIG. 5.—Phase diagrams ($P = 1^{d}19$) for the y, b, and u magnitudes, the $u - b$ color, and the Hβ index. Symbols as in Fig. 4.

line behavior in U Gem, which is thought to arise in an accretion ring about the white-dwarf component (Kraft 1962; Krzemiński 1965; Warner and Nather 1971).

Clearly, complete phase coverage for all the parameters is essential before the interpretation of σ Ori E can proceed further; it should be noted that six consecutive nights are required to cover the entire cycle once.

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Note added in proof.—Further *uvby*-β observations of σ Ori E obtained during 11 consecutive nights in 1975 December–1976 January confirm the presence of two eclipses in the light and color curves. (J. E. Hesser, N. R. Walborn, and P. Ugarte P., in press).

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