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A LARGE, PERIODIC VARIATION IN THE STELLAR WIND OF θ^1 ORIONIS C

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ABSTRACT

A period of 15.4 days, recently discovered by Stahl et al. from intensive monitoring of Hα emission in θ^1 Ori C during 1992–1993, has been found to phase large variations in the C IV $\lambda\lambda$1548, 1551 wind profile of this star previously reported from *IUE* high-resolution data obtained during 1978–1983. These stellar-wind variations are among the largest observed in O stars not known to be components of interacting binaries; the strict periodicity is unique among apparently single O stars and constitutes an important constraint on the unknown origin of the phenomenon.

Subject headings: stars: mass loss — stars: individual (θ^1 Orionis C)

1. INTRODUCTION

θ^1 Orionis C (HD 37022) is the principal ionization source of the Orion Nebula. It is of additional interest as a possible very young, zero-age main-sequence (ZAMS) O star, and because of the unusual variations observed in its optical spectrum during one-week intervals (Conti 1972; Walborn 1981). Large variations in its ultraviolet C IV stellar-wind profile were also reported by Walborn & Panek (1984) and Walborn, Nichols-Bohlin, & Panek (1985), but no temporal pattern could be discerned due to the sparse sampling (12 observations throughout 4.5 years). A very significant development is the discovery of a well-defined period of 15.43 ± 0.03 days in Hα emission from θ^1 Ori C by Stahl et al. (1993), who were able to obtain 47 high-resolution observations of the star during 48 consecutive nights. Application of this period to the available UV data immediately revealed a reasonable phase diagram for the C IV variation as well, the characteristics of which are thereby unique to date among O-type spectra and are presented here.

The spectral type of θ^1 Ori C is usually given as O6–7p (Morgan & Keenan 1973), where the peculiarity consists of excessively broad hydrogen lines, possibly related to extreme youth. (This point is relevant to estimates of the rotational velocity, as further discussed below.) However, Walborn (1981) observed the spectral type to vary from O6 to O4 during seven consecutive nights. Such variations were not seen by Conti (1972) or by Stahl et al. (1993), who both found a spectral type of O7.

2. DATA ANALYSIS

The 12 short-wavelength, high-resolution images of θ^1 Ori C obtained by the *International Ultraviolet Explorer* (*IUE*) are listed in Table 1. They were retrieved from the National Space Science Data Center archives for this analysis. The exposure times range from about 1 to 3 minutes through the large (L) and small (S) entrance apertures, respectively. The spectral data between 1520 and 1570 Å were normalized with a linear fit between the means of the fluxes in 4 Å bins centered on those two points. The echelle orders were spliced by the method of Barker (1984), and the data were rebinned to a uniform resolution of 0.25 Å. To investigate the C IV $\lambda\lambda$1548, 1551 profile variations described in the next section, SWP 14665 was selected as a reference spectrogram and subtracted from each of the others. The results for the "excess absorption" between 1530 and 1548 Å, which displays the most prominent variation, are also listed in Table 1. This difference feature measures about 500 mÅ in SWP 19606, which shows the least departures from SWP 14665, so that amount is taken as an upper limit to the errors in its equivalent widths. For comparison with the difference values, the total C IV wind absorption (plus blended photospheric lines) longward of 1530 Å in SWP 14665 is about 9000 mÅ.

The phases listed in Table 1 correspond to a period of 15.41 ± 0.02 days referred to 1978 Day 000.00 = JD 2443508.5. This value produced the smallest Lafler-Kinman (1965) parameter (0.584), although trial periods of 15.43 and 15.44 days were nearly as good (0.598); these were the three lowest points of a broad minimum. The formal uncertainty is smaller than that of Stahl et al. due to the longer time base, but the present result is not necessarily an improved determination of the period in view of the small number and density of observations. Unfortunately, the time difference is too great to permit phasing with the observations of Stahl et al.

3. C IV PROFILE DESCRIPTIONS

The 12 original C IV profiles are shown in phase order in Figure 1, and the difference spectrograms with respect to SWP 14665 similarly in Figure 2. Clearly there are two extreme profile states and some intermediate cases. At one extreme, well represented by SWP 14665, the strong, blueshifted absorption of the P Cygni profile has a steep shortward edge ending at about 1540 Å or -1600 km s^{-1}, although there may be some weaker absorption extending toward shorter wavelengths. At the other extreme, seen at phases 0.88–0.91, the higher-velocity absorption is much stronger, and the shortward edge rises more gradually until about 1530 Å or -3600 km s^{-1}. The latter corresponds to the terminal velocity of an early O star, but the unsaturated total absorption is weak at all

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TABLE 1

IUE SHORT-WAVELENGTH, HIGH-RESOLUTION IMAGES OF θ^1 ORIONIS C

Image Number (SWP)	Original PI	Aperture	Exposure Start (Year/Day/UT)	JD (2440000+)	Phase (15.41 days)	Excess Absorption (mÅ)
2768................	Savage	S	1978 Sep 26 10:57	3777.96	0.49	1384
2769................	Savage	S	1978 Sep 26 12:29	3778.02	0.49	1285
5017................	Schiffer	S	1979 Apr 24 20:56	3988.37	0.14	821
7481................	Canal	L	1979 Dec 23 13:22	4231.06	0.89	2186
9991................	Penston	S	1980 Sep 2 16:50	4485.20	0.38	643
13737................	Panek	L	1981 Apr 17 01:31	4711.56	0.07	1425
13798................	Panek	L	1981 Apr 24 19:26	4719.31	0.57	1436
14597................	Panek	L	1981 Jul 31 00:01	4816.50	0.88	2153
14665................	Bianchi	L	1981 Aug 5 19:12	4822.30	0.26	$\equiv 0$
15799................	Panek	L	1981 Dec 19 01:20	4957.56	0.03	1622
16232................	Patriarchi	L	1982 Feb 1 09:56	5001.91	0.91	2034
19606................	Panek	L	1983 Apr 2 01:07	5426.55	0.47	503

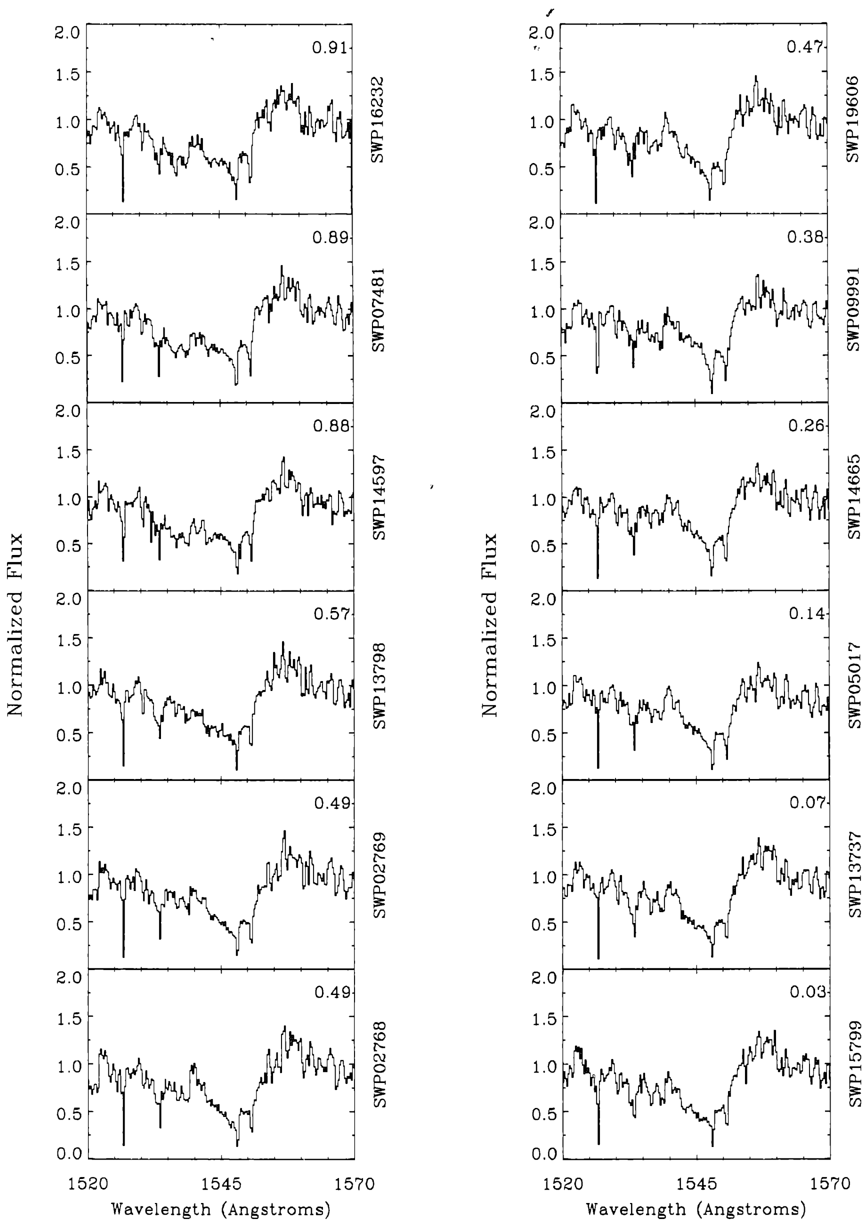

FIG. 1.—Rectified *IUE* high-resolution profiles of C IV λλ1548, 1551 in θ^1 Orionis C, ordered by phase on a period of 15.41 days. Interstellar lines of Si II λλ1526, 1533 and the C IV doublet are prominent in this wavelength range.

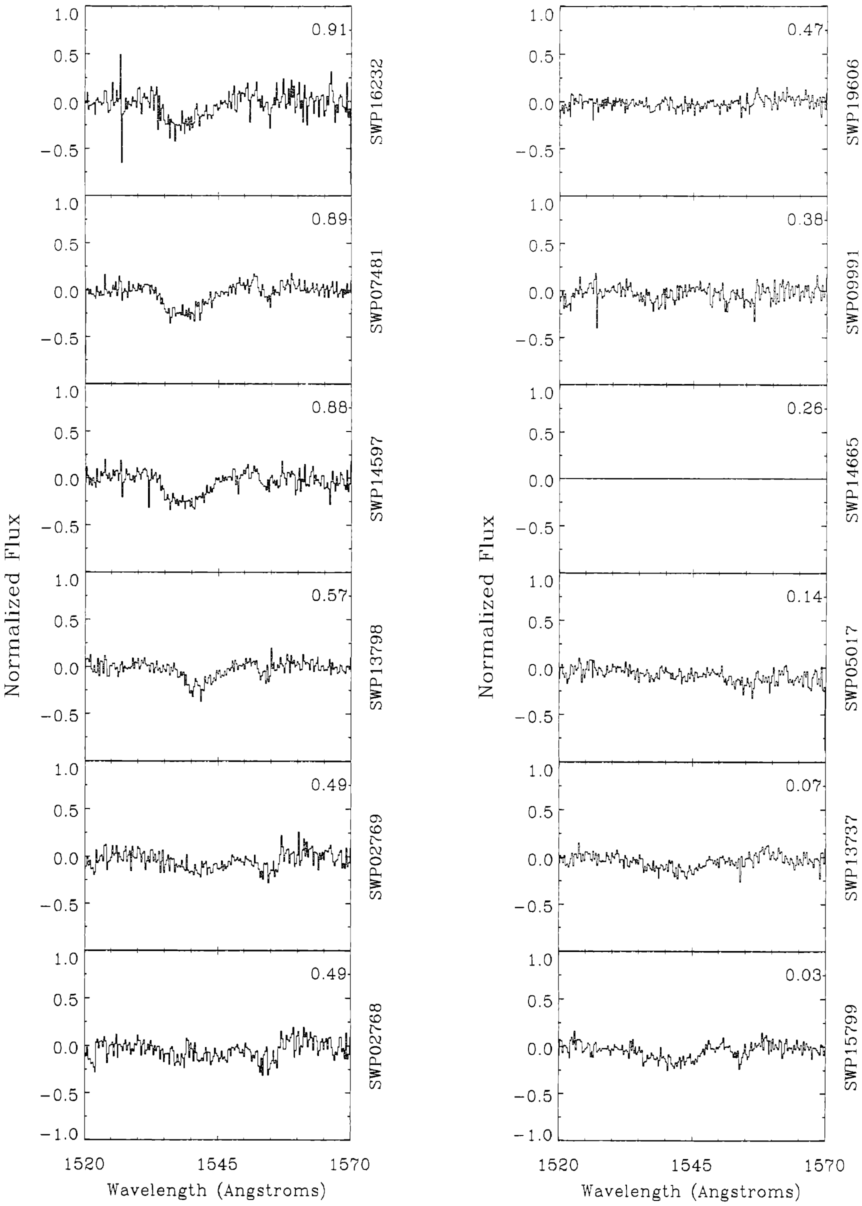

FIG. 2.—Difference profiles of C IV in θ^1 Ori C with respect to SWP 14665, ordered as in Fig. 1

phases compared with normal mid- to early-O spectra, as shown by Walborn & Panek (1984) and Walborn et al. (1985).

The difference profiles show several features, the most prominent being the excess absorption between 1530 and 1548 Å, which peaks at phases 0.88–0.91. Note that the three profiles in this phase range were obtained in different years (Table 1). The corresponding phase diagram is plotted in Figure 3. The wavelength of maximum absorption in this feature appears to move shortward between phases 0.49 and 0.91, although the effect may be due just to the strengthening higher velocity absorption. A second, narrower absorption feature between 1550 and 1560 Å evidently corresponds to a variable depression in the emission component of the P Cyg profile, most strongly between phases 0.49 and 0.91; the equivalent width of this feature ranges from 500 to 900 mÅ. In addition, excess emission can be seen in several profiles, sometimes on either or on both sides of the 1550–1560 Å absorption feature.

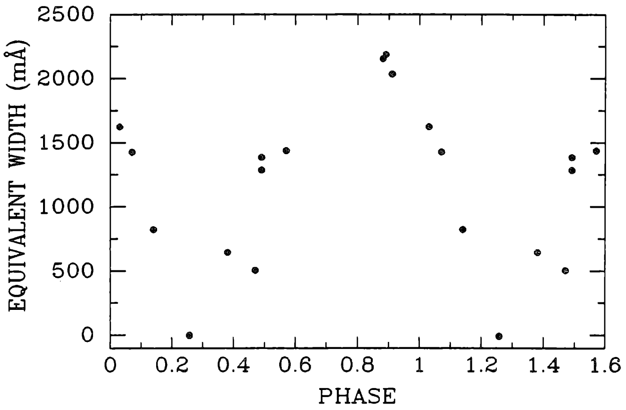

FIG. 3.—Phase diagram of the 1530–1548 Å excess absorption in θ^1 Ori C on a period of 15.41 days. The value from SWP 14665 at phase 0.26 is identically zero since it provides the reference profile.

While the above description of the profile variations is self-consistent, an alternative interpretation appears possible, namely that the stronger-absorption state is the baseline, and it is periodically filled in to varying degrees by an emission feature peaking at 1540 Å.

4. DISCUSSION

Evidently, the stellar wind of θ^1 Orionis C contains a substantial structural asymmetry and a clock mechanism which has maintained a stable modulation for at least 15 years. However, further observational information is required to support a plausible physical model of these phenomena. Stahl et al. (1993) also made the first detection of radial-velocity variations in θ^1 Ori C, but there is no relation to the period of the spectral variations. This star was identified as a short-term variable X-ray source by Ku, Righini-Cohen, & Simon (1982); further variability study would clearly be of interest. It has not been detected as a radio source (Felli et al. 1993, and references therein).

Some of the behavior of θ^1 Orionis C is reminiscent of the helium-rich, magnetic oblique rotator σ Orionis E (Walborn 1974, 1982; Shore & Brown 1990); magnetic observations of θ^1 Ori C may provide the key, as previously suggested by Walborn (1981) and by Stahl et al. (1993). A surface field of 1800 G, similar to those of the helium-rich stars, follows from equation 10 of Shore (1987), with the assumptions of corotation to 10 stellar radii, a 15.4 day rotational period, a mass-loss rate of $10^{-6.4}\ M_\odot\ \mathrm{yr}^{-1}$ (Howarth & Prinja 1989), and a terminal velocity of 3600 km s^{-1}. It should be noted that $v \sin i = 130$ km s^{-1} and $R = 8\ R_\odot$ as given for θ^1 Ori C by Howarth and Prinja imply an upper limit of 3 days to the rotational period; however, the line widths in this star may be partly due to a higher gravity or other effects related to extreme youth, compared to typical O main-sequence stars. Also, the extension of Hα emission wings to 400 km s^{-1} (Stahl et al. 1993) but C IV absorption to 3600 km s^{-1} is consistent with formation of the former nearer to the stellar surface, as expected from the nature of these transitions.

A physical relationship between the wind variations in θ^1 Ori C and the origin of variable discrete absorption components observed in many O-type winds (Howarth & Prinja 1989) is possible, although the strict periodicity in this star is distinct. The magnitude of the absorption variations in θ^1 Orionis C appears comparable to that of the broad Si IV $\lambda\lambda$1394, 1403 components seen in ξ Persei, as does the relationship between Hα and wind edge velocities, although the time scale is much shorter and not strictly periodic in the latter star (Prinja, Howarth, & Henrichs 1987; Henrichs, Kaper, & Nichols 1994). Also, Howarth & Prinja (1989) measured a narrow absorption component at -350 km s^{-1} in the N V $\lambda\lambda$1239, 1243 wind profile of θ^1 Ori C in image SWP 19606; we have not been able to discern clear variations in the N V profiles perhaps due to the greater observational difficulties at those wavelengths in *IUE* data (other resonance lines in the SWP range do not show wind effects in θ^1 Ori C, as expected for its spectral type). More intensive UV spectroscopic monitoring is essential to fill in the C IV phase diagram of θ^1 Ori C and further investigate the N V, quasi-simultaneously with optical coverage to elucidate the relationship between the stellar-wind-absorption and Hα-emission variations, and their physical interpretation.

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