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THE *IUE* MEGA CAMPAIGN: THE ROTATIONALLY MODULATED WIND OF ζ PUPPIS

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ABSTRACT

We discuss 16 days of intensive *IUE* observations of the Si IV doublet (λ1400) in the spectrum of the O4 I(n) f star ζ Pup. The data show continuous variability throughout the greater part of the blueshifted absorption. Time series analysis of these data reveals significant power at periods of 19.2 hr and 5.2 days, which we identify with the mean recurrence time of "discrete absorption components" (DACs) and the photospheric rotation period, respectively. These results indicate that the wind has a global longitudinal asymmetry (approaching a factor 2 in optical depth), possibly associated with large-scale magnetic structures, but suggest that the DACs are not directly associated with specific stellar longitudes in this star. There is no significant power in the lines at the 8.5 hr period identified in photospheric absorption-line variability, nor at the 16.7 hr period reported in X-ray observations.

Subject headings: stars: early-type — stars: individual (HD 66811) — stars: mass loss — ultraviolet: stars

1. INTRODUCTION

The star ζ Puppis (HD 66811) not only provides an archetype for O supergiants, but it is also one of the few O-type stars for which we can identify, a priori, both a probable rotation period, P_{rot}, and a period for photospheric line profile variability (probably associated with pulsation), P_{phot}. It also has well-documented stellar wind variability (e.g., Conti & Niemala 1976; Snow, Wegner, & Kunasz 1980; Prinja et al. 1992). Together with its brightness and convenient location, these factors led to its selection as one of three targets in the landmark *IUE* time series campaign described by Massa et al. (1995, hereinafter Paper I, the MEGA campaign).

Paper I describes the rationale for relatively long, intensive time series spectroscopic studies of early-type stars. Principal among the arguments in favor of observations extending over many days is that such observations provide, for the first time, an opportunity to look for stellar wind structures modulated on the rotation period. For ζ Pup we have a distance estimate (based on its low reddening and likely association with γ Vel; Brandt et al. 1971) and a direct (interferometric) determination of the angular diameter, θ_D (Hanbury Brown, Davis, & Allen 1974). These data lead to a value for the radius (see Table 1) that is consistent with values required by stellar wind models (Puls 1987) and with the *V*-band surface brightness implied by several concordant determinations of T_{eff}. Recent measurements of $v_e \sin(i)$ show a rather small spread and cluster around a value that is toward the upper end of the range observed for O stars; the presumption is, therefore, that $\sin(i) \simeq 1$. Combining the radius and projected equatorial velocity gives $P_{rot}/\sin(i) = 4.8$ days; there is an uncertainty of approximately 30% or more on this figure, given that there is *at least* a 25% uncertainty in the distance (e.g., Kudritzki et al. 1983), and approximately 10% uncertainties on $v_e \sin(i)$ and θ_D.

High-dispersion optical observations of ζ Pup show subtle (about 1%) variability in the absorption lines (Baade 1991). Time series analysis shows that this variability is associated with power at $P_{phot} \simeq 8.5$ hr (Baade 1991; Reid & Howarth 1995). This periodic signal may be associated with sectorial nonradial pulsations with $l = -m \simeq 2$. Although we loosely refer to these motions as "photospheric," it should be recognized that line formation probably takes place in regions where hydrostatic equilibrium is already a poor approximation.

2. OBSERVATIONS AND DATA REDUCTION

The data come from the MEGA time series campaign described in Paper I. We carried out an independent extraction of the data by using IUEDR (Giddings et al. 1995), instead of IUESIPS, in the manner described by Howarth & Prinja (1989). For well-exposed spectra, such as those discussed here, the differences in the reduced spectra are usually slight, the principal advantages of IUEDR being interactive adjustment of wavelength scales, to ensure internal consistency, and of the correction for "leakage" of flux into the background channels, carried out with a modified version of the Bianchi & Bohlin (1984) algorithm. The latter feature allowed us to recover good data for the full spectral range in SWP 53451, which SIPS failed to extract satisfactorily (Paper I), giving a total of 149 high-dispersion ($R \simeq 10^4$) spectra.

The star ζ Puppis was the first and last target to be observed during the MEGA campaign and so holds claim to the distinction of having—marginally—the longest intensive *IUE* time series of any star.

3. TIME SERIES ANALYSIS

In this Letter we concentrate on the behavior of the Si IV resonance doublet. This gives strong, but unsaturated, P Cygni features that are separated by approximately 2000 km s^{-1} ($\sim 0.8 v_\infty$).

A dynamic spectrum is shown in Figure 1; this is similar to Figure 3 of Paper I (and illustrates the continuously variable

[1] Guest Observer with the *IUE* satellite, operated jointly by NASA, ESA, and PPARC.

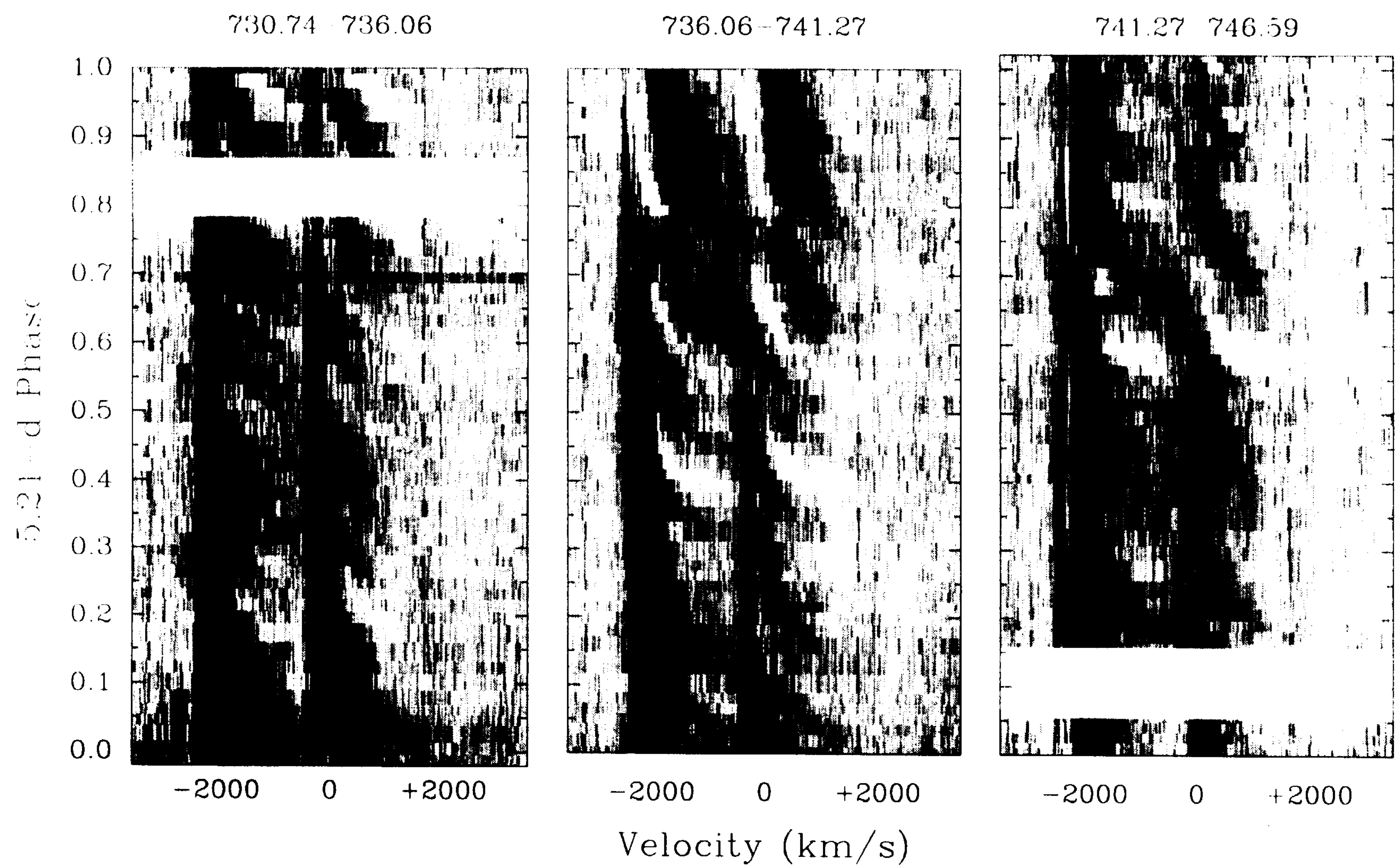

FIG. 1.—Dynamic spectrum for the Si IV λλ1393.8, 1402.8 doublet, shown as ratios with respect to a "minimum absorption" template; data are displayed linearly scaled in the range 0.5 (*black*) to 1.1 (*white*). White bars are due to gaps in the data run, and velocities are with respect to the blueward component. The data are shown organized into cycles of the 5.2 day rotation period; the least significant figures of the Julian Dates are given at the top of each panel.

TABLE 1

SOME BASIC PARAMETERS FOR ζ PUPPIS

Quantity	Value	Reference
Spectral type	O4 I(n)f	1
V	2.26	2
$(B-V)$	−0.27	2
$(U-B)$	−1.19	2
Angular diameter (mas)	0.42 ± 0.03	3
$v_e \sin i$ (km s^{-1})	210	4, 5, 6
Distance (pc)	460:	6, 7
v_∞ (km s^{-1})	2485	8
$T_{\rm eff}$ (kK)	42.0 ± 1.5	4, 6
$R_*/R_\odot$	20	3, 6, 7

References.—(1) Walborn 1972; (2) Johnson 1965; (3) Hanbury Brown et al. 1974; (4) Bohannan et al. 1986; (5) Conti & Ebbets 1977; (6) Kudritzki et al. 1983; (7) Brandt et al. 1971; (8) Prinja, Barlow, & Howarth 1990.

"discrete absorption components" [DACs] emphasized therein) but here is split into 5.2 days segments for reasons discussed below. The behavior of other lines formed in the supersonic portion of the wind is consistent with the Si IV doublet; in particular, there is no evidence for any differences in DAC velocities for different ions at any given time.

We have carried out a power spectrum analysis of these data by using the Lomb-Scargle periodogram (Lomb 1976; Scargle 1982; Horne & Baliunas 1986). Each *IUE* spectrum was first (arbitrarily) normalized to have a mean intensity level of unity across the entire wavelength range, and the power spectra was then calculated, wavelength by wavelength, from the "light curves" of intensity versus time. We verified that the normalization has no effect on the time series results and that no periodic signal is present in the normalizing factors (which show an rms dispersion of less than 2%).

Figure 2 shows the resulting power spectra assembled into a two-dimensional periodogram. The two most significant periods are at $P_1 = (5.21 \pm 0.71)$ days and $P_2 = (19.23 \pm 0.45)$ hr, where the errors represent the half-widths at half-maximum of the periodogram peaks. There is no significant power, at any wavelength, at periods close to $P_{\rm phot}$. (Low-frequency power is present at a period equal to the length of the data run and is therefore unlikely to be astrophysical in origin; there also appears to be power at $P = 2P_2$, only at about −2000 km s^{-1}.) The power at both P_1 and P_2 is confined solely to the absorption troughs of the doublet, with significant line profile variability from about −2600 km s^{-1} (in the redward component) to −800 km s^{-1} (in the blueward component). Following the methods of Howarth & Smith (1995), we deduce that there is no statistically significant variability outside the absorption region, with an upper limit to the rms dispersion of the normalized intensities of approximately 3%.

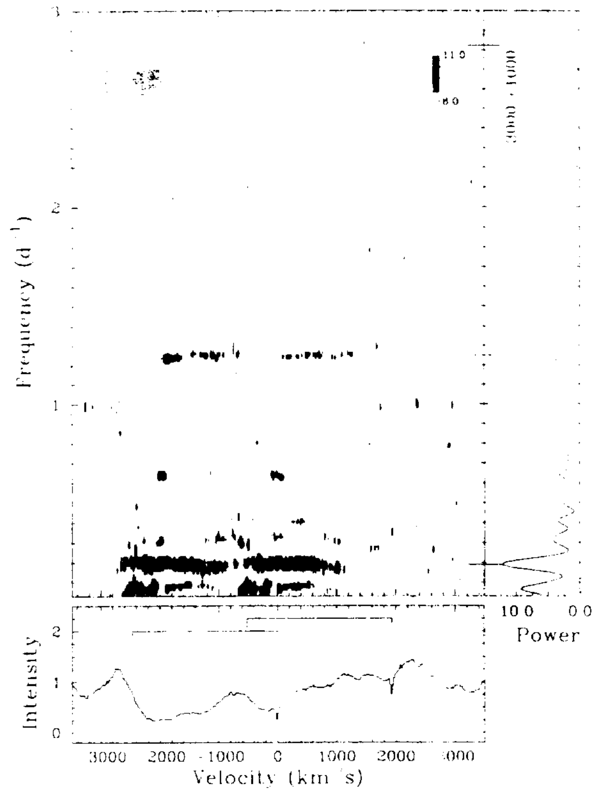

FIG. 2.—Two-dimensional Lomb-Scargle power spectrum of the data shown in Fig. 1. The main panel shows power as a function of velocity and frequency, linearly scaled over the range 8 to 11 (corresponding approximately to 5% and 0.1% "false alarm" probabilities for a single velocity). The bottom panel shows the mean spectrum, with horizontal bars running from zero velocity to v_∞ for each doublet component, while the right-hand panel shows the mean power per sample over the velocity range −3000 to +1000 km s^{-1} (with respect to the blueward doublet component). The long tick marks on the interface of the upper two panels indicate (*bottom to top*) periods of 5.2 days, 19.2 hr, 16.67 hr, and 8.5 hr. The first two periods are evident in the data, while the second two are not.

4. DISCUSSION

Figure 1 shows the data set divided into 5.2 day cycles, while Figure 3 shows the same data sorted by phase on P_1 and P_2. The 5.2 day period found in the P Cygni absorption-line strength is much longer than the flow time and is therefore unlikely to be directly related to any mechanism entirely intrinsic to the wind. On the other hand, it is within 10% of the anticipated photospheric rotation period. A plausible interpretation is, therefore, that this period is identical with the rotation period (and that $\sin i \simeq 1$). The observed power at this period then indicates that the wind is modulated, on a global scale, by a mechanism locked to the photospheric rotation. This modulation is evidently not the *dominant* source of variability in Si IV, which is principally characterized by the DACs, but its statistical significance (and hence the likelihood of its physical reality) is very high.

The optical depth variations on the rotation period range over a factor of about 1.3 on either side of the mean at around −2000 km s^{-1} in the blueward Si IV component (which is where the peak power—or maximum amplitude—occurs). This provides a guide to the associated mass-column variations. Since Si^{3+} is a minority ion formed primarily by recombination in stars as hot as ζ Pup, its relative abundance varies like density squared. The longitudinal density asymmetry is therefore probably also in the region of a factor 1.3—less than the rotationally induced equator-to-pole density asymmetry found by Harries & Howarth (1995), but nonetheless substantial.

The most obvious candidate for a mechanism responsible for the rotationally modulated component of wind variability is a weak magnetic field. The simplest configuration consistent with the data is a low-order (e.g., dipole) field offset from the

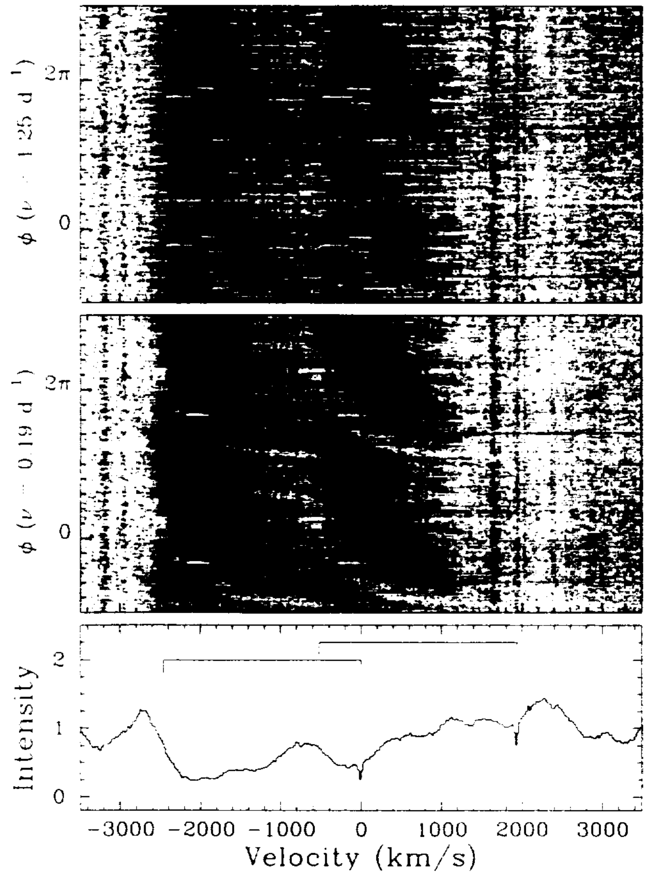

FIG. 3.—The data of Fig. 1 folded on the 5.2 day and 19.2 hr periods (frequencies 0.19 day^{-1} and 1.25 day^{-1}, respectively), shown over two complete cycles for continuity; zero phases are arbitrary. No interpolation or smoothing has been used in this figure.

rotation axis—a decentered oblique rotator (see Moffat & Michaud 1981). Decentering is required to produce a single "special" location on the star, rather than two indistinguishable poles, which would result in power at twice the rotation frequency. In such a model we might expect rotationally modulated changes in the maximum outflow velocity (fastest outflow along the magnetic poles), and there are indications of such a modulation in lines of greater optical depth. These data will be presented and discussed in more detail in a later paper.

The 19.2 hr period is identifiable with the mean recurrence time of the discrete absorption components visible in Figure 1. The identification is confirmed by stacking the spectra in phase (Fig. 3); this also confirms the impression given by Figure 1 that the variations on this timescale are not strictly coherent. Prinja et al. (1992) found a 16 hr recurrence period in previous *IUE* observations. That data set was much smaller than the one discussed here and is less amenable to time series analysis; nonetheless, a reexamination of the earlier data suggests that there may be real differences in the level of "activity" in the two samples. Berghöfer et al. (1995) report a 16.7 hr period in both Hα and in the 0.9–2.0 keV X-ray flux, which is close to, but significantly different from, the DAC recurrence period found here. By planting test signals, we determine that there is no sinusoidal signal present in our data at the Berghöfer period, with an upper limit to the semiamplitude of 2% of the continuum level.

The ratio of the DAC and rotation periods is probably not integer. From our own data we find P_1/P_2 = 6.51 ± 0.89, which is not conclusive; however, if we adopt as P_1 the consistent, but more precise, period of (5.025 ± 0.003) days found in Hα by Moffat & Michaud (1981), we then obtain P_1/P_2 = 6.27 ± 0.15, which differs from exactly 6 with approximately 97% confidence. Moreover, if the difference between DAC recurrence times reported here and by Prinja et al. (1992) is real, then it is unlikely that both are integral fractions of the rotation period. The implication of this assertion is that, in ζ Pup, the "seat" of any given DAC is unlikely to be located at a unique stellar longitude (contrary to the result found for HD 64760; Prinja, Massa, & Fullerton 1995).

Finally, there is no significant power in the UV wind-formed profiles at the frequencies previously identified in optical absorption-line variations (again with an upper limit to the semiamplitude of 2% of the continuum level). Thus, these data provide no evidence for direct driving of stellar wind variability by time-dependent velocity fields at the photosphere, although there is a claim for driven variability in Hα (Reid & Howarth 1995).

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