NASA-CR-203764

THE ASTROPHYSICAL JOURNAL, 452: L61–L64, 1995 October 10

THE *IUE* MEGA CAMPAIGN. MODULATED STRUCTURE IN THE WIND OF HD 64760 (B0.5 Ib)

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Received 1995 June 12; accepted 1995 July 18

ABSTRACT

We highlight systematic variability in the stellar wind of the early B type supergiant, HD 64760, whose UV line profiles were monitored for almost 16 days in 1995 January as part of the *IUE* "MEGA Campaign." The extensive coverage reveals a pattern of rapidly evolving discrete optical depth changes which typically migrate from ~ −200 km s^{-1} to ~ −1500 km s^{-1} in less than 12 hr. These features coexist with more slowly evolving structures lasting several days. Time-series analysis of the Si IV, Si III, and N V profile variations presents a clear 1.2 day periodicity, which is a quarter of the estimated maximum rotation period of HD 64760. The line profile changes are consistent with an interpretation in terms of a set of corotating wind features which occult the stellar disk at least 3 times during the observing run. These data are combined with UV observations collected in 1993 March to argue in favor of rotationally modulated wind variations in HD 64760.

The basic result of very regular, large-scale optical depth variations points to a "clock" whose origin is on the stellar surface, rather than a mechanism that is entirely intrinsic to the stellar wind.

Subject headings: stars: activity — stars: early-type — stars: individual (HD 64760) — stars: mass loss — ultraviolet: stars

1. INTRODUCTION

The primary motivation for the hot stars *IUE* "MEGA Campaign" (Massa et al. 1995a) was the need to examine the potential role of stellar rotation in modulating large-scale wind variability in stars of differing basic parameters. The inclusion of an early B type supergiant therefore provided an extension toward a lower effective temperature and luminosity, whilst offering the substantial advantage of sampling unsaturated wind-formed lines from a wide range of ionization stages (i.e., C II λλ1335, Al III λλ1860 to Si III λ1206, Si IV λλ1400 and C IV λλ1550, N V λλ1240). In addition, the UV photospheric silicon lines of B supergiants are sensitive temperature and surface gravity diagnostics (Massa 1989), and provide a probe of the wind-photosphere interface (Massa, Shore, & Wynne 1992).

The B supergiant HD 64760 [B0.5 Ib, $v_e \sin(i) \sim 238$ km s^{-1}] was selected on the basis of results obtained during a 6 day *IUE* monitoring campaign carried out in 1993 March (Massa, Prinja & Fullerton 1995). The star revealed continuous and substantial wind variations on hourly timescales, with the presence of recurrent discrete optical depth enhancements; these are the recognized hallmarks of wind structure in OB stars.

The stellar wind of HD 64760 was monitored for 15.8 days during the *IUE* MEGA campaign in 1995 January, yielding 148 spectra. A gray-scale image representation of changes in the N V λλ1238.8, 1242.8 profile is shown in Figure 1 (see also Massa et al. 1995a). The image shows individual profiles normalized by a minimum absorption (maximum flux) template, such that darker shades represent greater optical depths. The stellar wind of HD 64760 is remarkably active, with the presence of two principal types of structure which coexist on separate timescales; (1) several fast moving features are seen as almost "horizontal" tracks in Figure 1. They span most of the absorption trough from initial appearance redward of ~ −200 km s^{-1} to the blue absorption edge at −1500 km s^{-1}. Variability at the 15% level is detected down to ~ −150 km s^{-1}, (2) two slower moving discrete absorption components are also evident, the first of which is present at the start of the run at ~ −1100 km s^{-1}, and migrates to the profile edge during the next 9 days. A second similar feature is observed shortly after the data gap at about 11 days into the campaign. An essentially one-to-one correspondence (in incidence and velocity) is noted between all these N V features and episodes in Si III λ1206, Si IV λλ1400, and C IV λλ1550 (see, e.g., Massa et al. 1996).

We highlight in this Letter evidence for a connection between the wind activity in HD 64760 and the stellar rotation timescale.

2. CHARACTERISTICS OF THE WIND VARIABILITY

2.1. *Periodicity*

It is already fairly clear from Figure 1 that the faster migrating structures, when monitored over such an extensive

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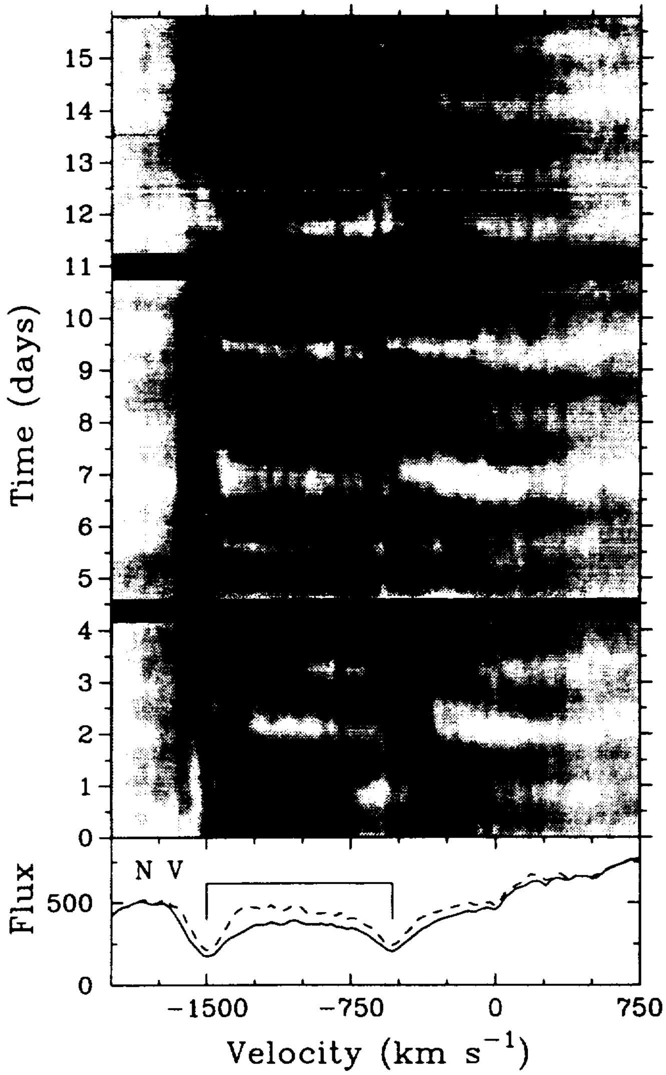

FIG. 1.—Gray-scale representation of the N v λλ1240 line profile changes, normalized by a minimum absorption template. Darker shades represent greater optical depth with respect to the template. Linear interpolation is used in the "time" axis. The mean N v profile from the time series (*solid line*) and the minimum absorption template (*dashed line*) are shown in the lower panel. The doublet separation is also indicated.

period, reveal a systematic pattern, with at least 13 episodes present over ~15.8 days. We performed time-series Fourier analysis of the wind variations in HD 64760 using the iterative CLEAN technique of Roberts, Lehár, & Dreher (1987). As an example, we show in Figure 2 (*top*) a CLEANed power spectrum based on the N v λ1242.80 mean flux between −600 and −200 km s^{-1}. The two frequencies that persist over most of the N v (and Si III and Si IV) absorption troughs are at ~0.835 and ~0.418 cycles day^{-1}, and correspond to periods of ~1.2 and ~2.4 days, respectively. We estimate that the maximum stellar rotation period of HD 64760 is ~4.8 days [for $v_e \sin(i)$ = 238 km s^{-1} and radius = 22.5 $R_\odot$; see Massa et al. 1995b]. It is reasonable to consider that the inclination, *i*, is close to 90 degrees since HD 64760 is one of the most rapidly rotating stars of its spectral class. The periodic nature of the line profile variations in HD 64760 is therefore an integral fraction of the estimated rotation period.

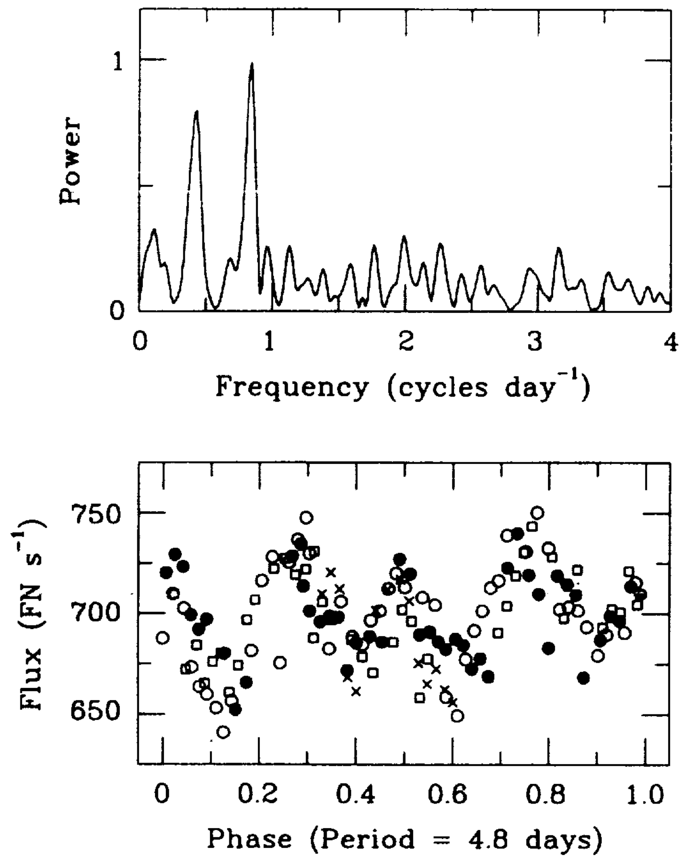

FIG. 2.—(*top*) CLEANed time-series power spectrum for N v λ1242.80 mean fluxes between −600 km s^{-1} and −200 km s^{-1}. The strongest peaks correspond to periods of 1.2 and 2.4 days. (*bottom*) The lower panels show the N v fluxes phased onto the maximum rotation period of HD 64760, ≈4.8 days. Sequential 4.8 days time blocks are shown as filled circles (0 to 4.8 days), open circles (4.8 to 9.6 days), squares (9.6 to 14.4 days), and crosses (more than 14.4 days).

Furthermore, the data are consistent with an interpretation that we are in fact seeing the repetition of a pattern on the rotation period. The observed N v λ1242.80 flux between −600 and −200 km s^{-1} is plotted in Figure 2 (*bottom*), phased on a 4.8 day period. We have differentiated in the figure between data collected in sequential blocks of 4.8 days. Therefore for an adopted period of 4.8 days (i.e., assuming that the rotational axis of HD 64760 is nearly perpendicular to our line of sight), the data suggest that the same set of co-rotating features occulted the stellar disk at least 3 times during the observing run.

At the very least, the data from the MEGA Campaign unambiguously demonstrate the extremely regular incidence of substantial structures in the stellar wind of HD 64760, which persist over several rotation cycles.

2.2. *Long-Term Behavior*

The systematic wind behavior of HD 64760 during the *IUE* MEGA Campaign in 1995 January may be compared to results from the 6 day *IUE* monitoring carried out in 1993 March by Massa et al. (1995b), to examine the persistent role of stellar rotation. Although a time-series Fourier analysis of the 1993 data set does not reveal a frequency dependence at the 1.2 day period, the profile variations observed in 1993 are consistent

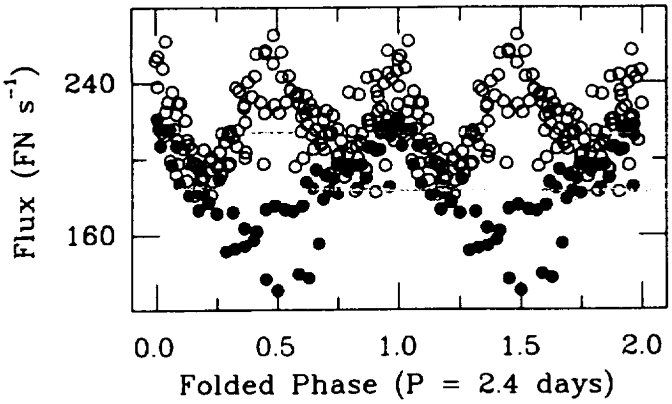

FIG. 3.—Mean Si IV λ1393.76 flux between −600 km s^{-1} and −200 km s^{-1} phased over two cycles of the 2.4 day period for data from the 1995 *IUE* MEGA campaign (*open circles*) and 1993 March (*closed circles*).

with periods of 2.4 or 4.8 days (i.e., 2 or 4 times the 1.2 day period). We show, for example, in Figure 3 the observed Si IV λ1393.76 flux between −600 and −200 km s^{-1} for the 1993 and 1995 data sets, phased on a 2.4 day period. It is conceivable then that the line profile variations evident in 1993 are also modulated on the stellar rotation period. Data from the two epochs constrain the coherence time for the cyclic profile behavior to between ~16 days and 21 months. Note also that there are substantial differences between the detailed nature of the profile changes between these two epochs. In particular Massa et al. (1995b) highlight a "main event" in the 1993 time series, which represents a particularly large increase in wind absorption strength, the onset of which had a unique correspondence to disturbances evident in the Si III λ1300 photospheric triplets, the C III λ1247 photospheric singlet, and the low-lying resonance lines due to C II λλ1335 and Al III λλ1860. An event of this nature in not obvious in the larger 1995 data set.

It is interesting that these continuous and extensive wind variations coexist with established time-independent relations such as the dependence of the OB star mass-loss rate on luminosity, and the success of spectral classifications based on wind-line morphology. The time-independent results rely of course on the notion of a meaningful, average "underlying" wind. In this connection, we show in Figure 4 the respective mean Si IV profiles derived from the 148 spectra in 1995 and the 56 spectra from 1993 (the latter is linearly shifted by ~10% to match the 1995 continuum level). Despite the extensive and differing time-dependent behavior evident in these data sets, the overall mean profiles are remarkably similar.

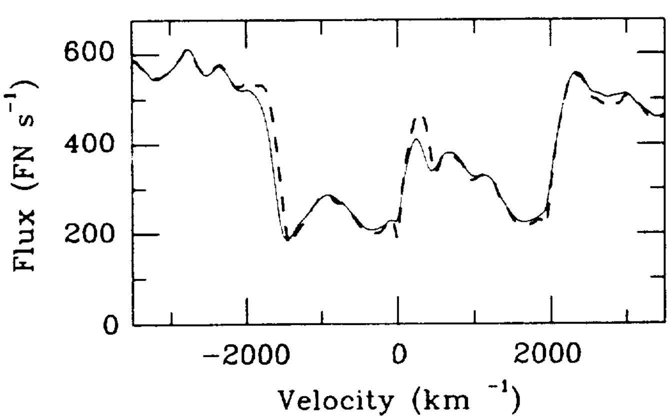

FIG. 4.—There is a remarkable similarity between the mean Si IV λλ1400 line profiles of HD 64760 from the 1995 January (*solid line*) and 1993 March (*dashed line*) time series data sets.

2.3. *Properties of the Modulating Structures*

We highlighted in § 1 that two types of basic wind structure coexist in HD 64760 on different timescales. The faster moving features provide the periodic behavior (§ 2.2). Their velocities change between −200 and −1500 km s^{-1} in less than 12 hr. The corresponding full-width at half-maximum varies from ~1000 km s^{-1} to less than 350 km s^{-1}. The mean accelerations of these features range between 1.0×10^{-2}–1.8×10^{-2} km s^{-2}; these values are in close agreement with those predicted by the canonical, $v(r) = v_\infty \ (1 - R_*/r)^\beta$, velocity-law parameterization, for $\beta = 0.8$–1.0. (We adopt a terminal velocity, v_∞, ~1550 km s^{-1}). In a few cases the migrating features appear to exhibit a *redward* motion at the lowest velocities (see, e.g., the episodes at $T \sim 2.7$ and 7.5 days in the Si IV gray-scale image of Massa et al. 1995a). We are currently exploring periodogram techniques to analyze this behavior. Assuming plane-parallel geometry and Gaussian model profiles (see, e.g., Howarth & Prinja 1989), we estimate that the Si^{3+} column density changes in individual episodes between $\sim 4 \times 10^{13}$ to 3×10^{14} cm^{-2}. The relative ionization behavior of the features is being examined in our ongoing analysis of this rich data set.

The two slower moving discrete absorption components evolve from ~−1000 km s^{-1} (at $T = 0$ days and ~11.3 days in Fig. 1; see also Massa et al. 1995a) to ~−1500 km s^{-1} over several days. The acceleration of these features decreases from $\sim 9 \times 10^{-3}$ km s^{-2} at ~−1000 km s^{-1} to less than 3×10^{-3} km s^{-2} blueward of −1350 km s^{-1}. These values are closer to those predicted by velocity laws with β indices of 3 or 4. The two features are narrower in velocity space (FWHM ~150–300 km s^{-1}), with Si^{3+} column densities varying between $\sim 2 \times 10^{13}$ cm^{-2} and 6×10^{13} cm^{-2}.

3. DISCUSSION

The extensive, 15.8 day, UV spectroscopic monitoring of the stellar wind of HD 64760 during the *IUE* MEGA Campaign in 1995 January has shown that the recurrent large-scale wind structure is very regular. Time series analysis reveals a 1.2 day periodicity, which is a quarter of the estimated maximum stellar rotation period. These data, and a shorter UV time series of HD 64760 from 1993 March, are consistent with an interpretation that HD 64760 has a rotationally modulated stellar wind.

These results lead us to conclude therefore that the hot, stellar wind is directly affected by the influence of a "clock" or pattern on the stellar surface. It is difficult to picture for example how the observed regular variations can be obtained via a mechanism that is entirely intrinsic to the wind. The modulated wind structures likely relate to variations in the photosphere of the star. A possibly pertinent model arises from Mullan's (1984) discussion of corotating interaction regions (CIRs), created at the interface of fast and slow streams in the wind, which are rooted (in some manner) at the photosphere. Numerical simulations of similar corotating stream structures have recently been explored by Cranmer & Owocki (1994). Note, however, that the models predict evolutionary timescales for the streams which are comparable to those of the two slow-moving structures observed in HD 64760, and not the dominant, rapidly evolving features.

Two possible sources for photospheric modulation in early-type stars are velocity fields due to one or more modes of stellar pulsation (e.g., Jerzykiewicz 1994) and inhomogeneities due to magnetic fields (e.g., Bohlender 1994). Note that for both cases the precise causal connection (if any) to outer wind phenomena in luminous, massive stars is not known. For the particular case of HD 64760, there are no published reports confirming photospheric pulsational behavior, although we are currently analysing a suitable high-quality optical spectroscopic data set to test for periodicity in the photospheric absorption lines. Ordered magnetic fields are not normally associated with hot OB stars with large radiative zones. Observational surveys (e.g., Barker 1986; Bohlender 1994) have not yet revealed any firm detections of magnetic fields at the 300 G level in normal, single OB stars. The observed optical depth variations in the UV wind lines of HD 64760 typically depress the local continuum by more than 20%–30% between -600 to -200 km s^{-1}. In terms of "magnetic spots" therefore individual features would have to cover a substantial portion of the stellar disk, and yet enter and leave totally the line of sight in a fraction of the rotation period. The observation that the wind variability timescale in HD 64760 is an integral fraction of the rotation period also implies that the sources of the disturbances must be equally spaced across the surface of the star.

The *IUE* MEGA Campaign has uniquely demonstrated the presence of highly modulated, evolving wind structure in early-type stars. The origin of this behavior likely resides at the stellar photosphere. The precise physical mechanism is now awaiting detailed investigation.

We gratefully acknowledge financial support for this project from the Royal Society (R. K. P.), and NASA grants NAS5-32782 (D. M.) and NAGW-2624 (A. W. F.) Many thanks also to Matthew Dalton, Martin Clayton and Joy Nichols for their help in handling and reducing the *IUE* data.

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