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Short-Term Wind and Photospheric Activity in Be Stars Deduced from Campaigns with the *IUE* Spacecraft

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Abstract.
From 1985–96 twelve multiwavelength campaigns on 15 Be stars were carried through using data from the *IUE* spacecraft to study the phenomenon of short-term spectroscopic and photometric variability. Highlights from recent work on this database are presented here. Three classes of variability have been identified: 1) The FUV flux and wind strength are correlated, 2) The FUV flux varies cyclically but wind variability if present does not correlate with the flux, and 3) The wind strength cyclically varies but does not correlate with light variations. For Class 1 the period is usually less than the star's expected rotational period, but for Classes 2 & 3, the period is sometimes close to P_{rot}. We have employed a cross-correlation technique to extract information on the nature of the line profile variability (*lpv*). Evidence for nonradial pulsations (NRP) in low-order modes is found for objects in Classes 1 & 2, the light variations appear to be caused by a modulation of the star's photospheric temperature, and the hot crest of the NRP wave is in front when the star is bright. For Class 1 stars the wind is enhanced over the hot crest. The mass loss in Class 3 may originate from a localized active region on the star and the importance of NRP in these stars remains unknown.

1. Motivation for the *IUE* campaigns

Community interest in short-term spectroscopic and photometric variability in Be stars essentially began in 1981. Although there were isolated reports of photometric variations on a time scale of 2^d prior to this date (Percy 1987), it seemed to be the papers on rapid variability in λ Eri and 28 (ω) CMa by Bolton (1982) and Baade (1982) at IAU Symposium No. 98 and the Nice Workshop on Pulsating B Stars that called our attention to the possible importance of this activity in the Be phenomenon. In the decade to follow two models emerged to explain short-term variability in Be stars, nonradial pulsations (NRP) and rotational modulation of co-rotating structures near the surface (RM). To this date no consensus has been reached, and both models are still debated (Baade & Balona 1994 and discussion in this proceedings).

Table 1. The *IUE* Campaign Stars[a]

Star	Sp. Type[b]	Observation Date[c]	FUV Flux/Wind Period (d)	CCF Period Mode[d]	Class[e]
μ Cen	B2 IVe	85/179 (16)	0.50±0.10 (f)	...	2
28 Cyg	B3 IVe	85/272 (12)	...	...	1
o And	B6 IIIe-sh	87/215 (12)	1.57: (f)	*s*	*u*
λ Eri	B2 IVe	87/309 (40)	0.70±.02 (f)	0.69±.12 (2)	2
ω Ori	B2 IIIe	87/309 (40)	1.0: (w)	*s*	3
ϵ Cap	B3 IIIe-sh	88/274 (40)	0.98±0.02 (f,w)	0.95±.27, *s*	1
28 Cyg	B3 IVe	89/263 (56)	0.65±0.02 (f,w)	0.68±.11 (2)	1
η Cen	B2 IVe	91/088 (64)	0.63±0.01 (f,w)	0.61±.08 (2)	1
48 Lib	B3 IVe-sh	91/089 (64)	0.4: (f)	...	*u*
ζ Tau	B1 IVe-sh	91/280 (56)	0.81±0.05 (f)	0.81±.16 (2)	2
ψ Per	B5 IIIe-sh	91/280 (56)	1.04±0.04 (w)	...	3
2 Vul	B0.5 IV	92/257 (24)	0.35: (f)	0.3±.1, *s* (4:)	2
120 Tau	B1.5 IVe	93/054 (16)	0.5: (f)	0.73±.67, *s*	2
EW Lac	B3 IVe-sh	93/249 (24)	0.50: (f)	0.35±.07, *s*	*u*
α Eri	B4 Ve	95/250 (64)	1.27±0.05 (f)	1.26±.09 (2)	2
λ Eri	B2 IVe	95/250 (64)	1.0±0.1 (w)	0.70±.10 (2)	2
DU Eri	B1 Ve	95/250 (64)	1.2±0.1 (f)	0.61±.08 (2:)	2
ω Ori	B2 IIIe	96/033 (72)	1.21±0.03 (w)	1.28:, *s*	3

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[a] G. J. Peters and/or H. F. Henrichs (NASA/VILSPA) Principal Investigator

[b] From Slettebak (1982)

[c] Year and Day number for start of campaign. Data sets for 28 Cyg, both campaigns, *o* And, and ϵ Cap contained gaps of 8–16 hours. Duration of campaign in hr is given in parentheses.

[d] $\ell=-m$ given in parentheses is tentative; *s* indicates that variable shell features interfered with interpretation of CCF data.

[e] *u* means that the behavior is unclassified. The usual cause is ephemeral shell activity masking underlying photospheric activity.

Informal discussions during IAU Colloquium No. 92 (Slettebak & Snow 1987) led to the question of whether there is a wind/photosphere interaction in the Be stars that display short-term variability. *Is there evidence in the FUV to support or refute the NRP hypothesis? Is the mass loss related to underlying NRP? Is NRP important in driving the mass loss in Be stars?* To address these questions we embarked on a series of multiwavelength campaigns. Typically a campaign would consist of a 24–72 hour interval of uninterrupted, repeated *IUE* observations that were supported by simultaneous optical photometry, high resolution spectroscopy, and polarimetry and sometimes FUV photometry from the *Voyager UVS*. The campaign chronology is summarized in Table 1. Other *IUE* campaigns were undertaken by Doazan et al. (1985, wind variability in 59 Cyg), Sonneborn et al. (1988, mass loss in ω Ori), Smith & Polidan (1993, dimple transients in λ Eri), Smith, Robinson, & Hatzes (1998, co-rotating structures in

γ Cas). In this paper we present highlights from our recent studies of the entire *IUE* database on short-term variability in Be stars.

2. Analysis of *IUE* Data

IUE images processed with the NEWSIPS software were obtained from the NSSDC archives. Equivalent widths (EW) of wind and photospheric features were measured and fluxes binned using standard IDL programs produced by the *IUE* Data Analysis Center (IUEDAC).

To study the nature of the photospheric line profile variability (*lpv*), simultaneous optical spectra with high resolution and S/N were obtained for many stars from which we able to confirm NRP, determine periods, ephemerides, and pulsation modes (Hahula & Gies 1994). However, we were unable to secure such data for some of the program stars, and diurnal gaps in the coverage for those that were observed and poor weather produced bothersome clustering of the data in phase that in some instances compromised our investigation. To circumvent this problem we have employed a new technique of analyzing *IUE* data using cross-correlation functions (CCFs). For an individual photospheric line, the *IUE* data are too noisy to reveal profile distortions due to NRP, but Penny (1996) demonstrated that the CCF formed by cross-correlating an *IUE* HIRES image of a known nonradial pulsator (e.g. ζ Oph) with that of a sharp-lined star of comparable spectral type shows the "bumps" that look like those seen in the high resolution optical line profiles. Following the success of a similar study of the *lpv* in the nonradial pulsator ϵ Per (Gies et al. 1999), we have formed CCFs for all of the campaign stars and analyzed their variations across the photospheric line profile using the Fourier-time series methods of Gies & Kullavanijaya (1988). All wind, shell, and interstellar lines were omitted from the analysis. Thus information on the wind and photospheric activity in the stars is derived from the same dataset, a clear advantage in this type of investigation.

3. Results

From the *IUE* data we were able to identify three classes of variability: 1) The FUV flux and wind absorption are correlated and vary cyclically, 2) The FUV flux varies cyclically but wind variability if present appears random and does not correlate with the flux, and 3) The wind strength cyclically varies but does not correlate with light variations. We have selected representative examples from the three classes of behavior and discuss these objects in more detail below. For all the program stars, periods found from the analysis of the flux, wind, and CCF variations and preliminary assessments of NRP modes and the star's class of variability are listed in Table 1.

3.1. Class 1: 28 Cygni

The best example of Class 1 behavior is seen in 28 Cyg. The FUV flux, wind, and photospheric variability shown in Fig. 1 is rather typical of objects in this class. The flux data are from *IUE* HIRES data binned in 10Å intervals. The binned data confirm that the amplitude of the FUV light curve increases with decreasing

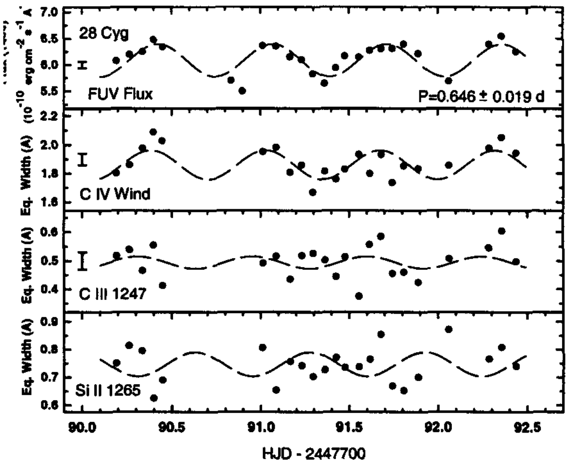

Figure 1. Photometric, wind, and photospheric activity in 28 Cyg during the 1989 September campaign. The *dashed* lines are sine curve fits to the 1450 Å flux and the EWs of the C IV wind and C III/Si II photospheric lines.

wavelength and imply that the photospheric temperature is modulated by 500–750 K (cf. a similar study of η Cen, Peters 1998). The light curve seen at 1450Å is representative of the FUV flux behavior. A sine curve fit to the 1450Å flux curve reveals a modulation of ~10% and a period of 0.65±0.02 d. The period found from the fit to the 1450Å light curve was then adopted for the sine curve fits to the EWs of the C IV 1550Å wind and C III 1247Å and Si II 1265Å photospheric lines shown in Fig. 1. Note the strong correlation between the EW of the C IV wind feature and the FUV flux. Note also that the EW behavior of the temperature sensitive photospheric C III and Si II features are possibly anti-correlated, as one would expect for temperature variations in an early B star. Based upon calculations made using the code SYNTHE (Kurucz 1994) and Kurucz (1993) model atmospheres, the observed variations in C III and Si II imply an average photospheric temperature modulation of ~500 K, in good agreement with the value obtained from the FUV flux curves.

The temporal behavior of the CCF in 28 Cyg is shown in the gray-scale plot in Fig. 2. The darkness of the gray-tone represents the deviation of the CCF for an individual observation (indicated by the arrows on the right axis) from the mean CCF shown in the lower panel. A darker gray-tone indicates more line absorption relative to the average CCF. The conspicuous diagonal stripes are a signature of NRP (Gies & Kullavanijaya 1988, Gies 1996). Note that the dark stripes (absorption "bumps") cross the center of the line very near the times of maximum in the FUV light curve. Our time series analysis of the data produced the periodogram shown in Fig. 3a. The dominant period is 0.68±0.11 d, which agrees within errors with the periods from the 1450Å light curve and optical data (0.64±0.06 d, Hahula & Gies 1994; 0.69±0.02 d, Peters & Penrod 1988). The power in the periodogram is concentrated on the wings of the line profile (cf.

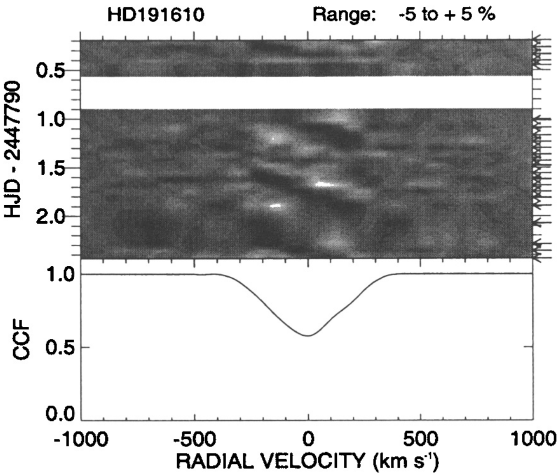

Figure 2. The temporal variation in the CCF in 28 Cyg.

also upper panel of Fig. 3b). This is a hallmark of NRP in a low-order mode in which horizontal motions dominate (Gies 1994). Following Gies & Kullavanijaya (1988) the pulsation mode can be estimated from the difference in the phase of the complex power spectrum across the line profile (blue-red): $|m| = 2\Delta\phi$. From Fig. 3b (lower panel), the range in complex phase indicates $|m| \sim 2$.

3.2. Class 2: α Eridani

α Eri is one of several Be stars that display well-defined (sometimes sinusoidal) light curves in the FUV but no obvious cyclic variability in the C IV wind line. Often the wind strength does appear to vary but not in an organized fashion. We refer to these stars as Class 2 objects. The flux and wind behavior in α Eri are shown in Fig. 4a. Fitting a sine curve to the 1450Å flux data we find a period of 1.27±0.05 d. A similar period (1.28±0.02 d) was discovered in 900–1280Å data obtained with the *Galileo* spacecraft (Holberg et al. 1999). The amplitude of the FUV light curve decreases with increasing wavelength and a fit of the variability using Kurucz (1994) models suggests a ΔT of 300–500 K. Although the EW of the C IV wind feature showed $\sim 4\sigma$ variation during the *IUE* run, it was not correlated with the FUV flux.

The CCF analysis of α Eri reveals strong evidence of NRP. The temporal behavior, shown in the gray-scale plot in Fig. 4b, displays the classic blue-red motion of absorption "bumps" in the line profile. Comparing Figs. 4a and 4b, it is clear that these bumps crossed the line center when the star was bright (observations 3, 14, 23+). The time series investigation reveals one dominant period at 1.26±0.09 d, in excellent agreement with the *IUE* and *Galileo* flux data and optical photometry (Balona & Englebrecht 1986). The periodogram shows that most of the power is found in the line wings and the calculation of the complex phase across the line profile at the above frequency suggests ℓ=1–2.

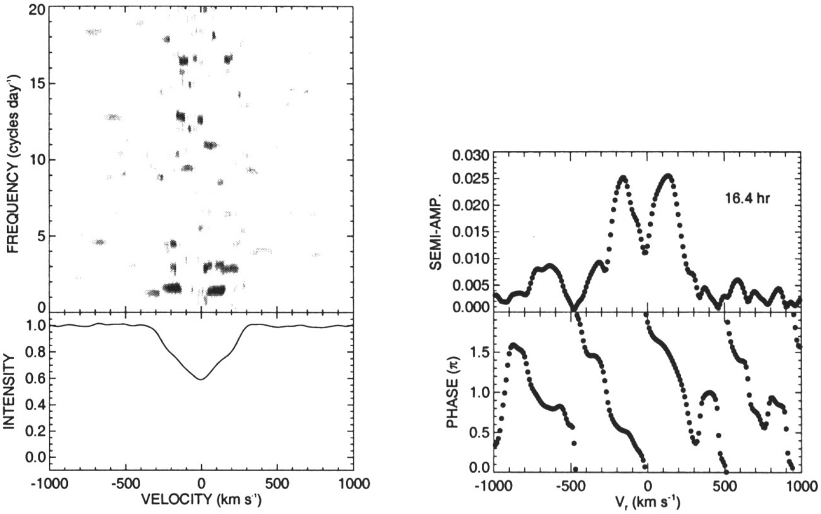

Figure 3. a. *left*: CLEANed periodogram for 28 Cyg. The density in the signal is proportional to the power. The mean profile appears below. b. *right*: the power and phase across the line profile for the dominant signal.

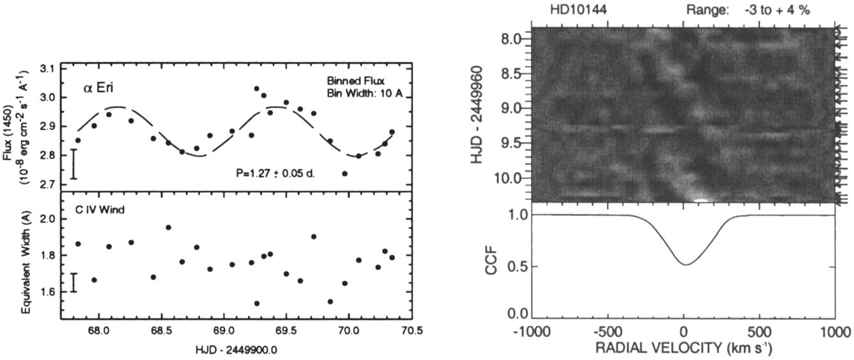

Figure 4. a. *left*: The light curve at 1450Å in α Eri compared with the EW measurements of the C IV wind feature. The dashed line is a sine curve fit to the flux data. b. *right*: Gray-scale display, as in Fig. 2, of the CCF behavior in α Eri.

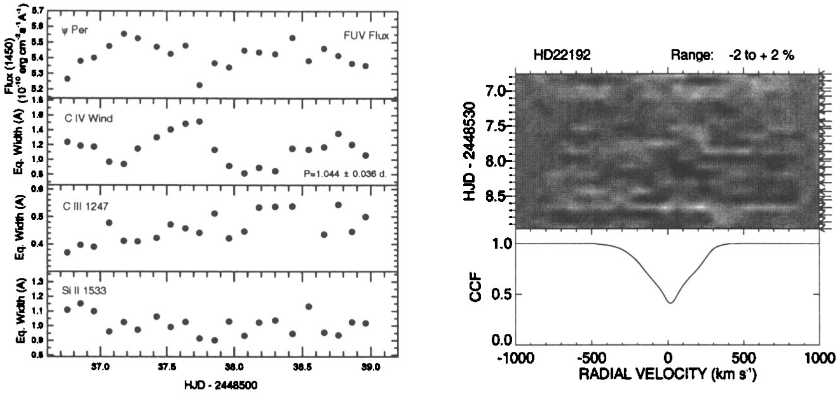

Figure 5. a. *left*: Behavior of the FUV flux and wind in ψ Per. The EW of the C IV wind feature varied cyclically by ~65%. b. *right*: The behavior of the CCF in ψ Per. Note the lack of a pattern.

3.3. Class 3: ψ Persei

The Be stars in Class 3 display cyclic variability in their winds. The FUV flux either varies apparently randomly or remains statistically constant. The most striking object in this class is ψ Per whose wind is modulated by ~65% in a period of 1.04 d (cf. Fig. 5a, Peters 1994). The CCF analysis of such objects usually shows no evidence for traveling absorption bumps in the line profile, but sometimes there is ephemeral shell activity. The CCF for ψ Per shown in Fig. 5b is typical for Class 3. No temporal pattern is evident.

4. Summary

Analysis of *IUE* data on 15 Be stars from 12 campaigns has revealed three classes of behavior:

1. Objects in Class 1 show correlated FUV flux/wind variability with a period that is usually less than the time expected for the star to rotate once on its axis. The light variations appear to be caused by a modulation in the star's photospheric temperature. Time series analyses of the cross-correlation functions from the *IUE* data suggest that these stars are nonradial pulsators with low-order modes. The absorption "bumps" in the photospheric line profiles seem to cross the center of the feature when the star is brightest. This corresponds to the transit of a hot crest of an NRP wave past the stellar meridian oriented toward our line-of-sight. The observed correlated behavior between the FUV flux and the wind implies that mass loss is enhanced over the hot crest.

2. Class 2 stars display well-defined FUV light curves. If variations are seen in the wind, they appear to be random. These objects show evidence of NRP in low-order modes. Periods can be shorter or comparable to the star's expected rotation period.

3. Cyclic wind variability, typically non-sinusoidal, is seen in Class 3 objects, but FUV flux variations are at best random. As the periods tend to be comparable to the expected rotation period of the star, the phenomenon could be caused by a localized region of mass loss sweeping past our line-of-sight as the star rotates. NRP could be masked by wind and shell activity but its role, if any in this class stars, remains unknown.

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Discussion

C. Aerts: According to me, there is no evidence whatsoever of having found NRP in the stars. You deduce this from the gray-scale pictures, but the detected variations are not modeled properly and any other model can explain the data equally well.

G. Peters: We base our conclusions concerning NRP on several observations, including the behavior of the traveling absorption "bumps" in the lines and the times that they tend to cross line center (when the star is bright). Nevertheless, we have cautioned the community that our interpretations of the data, including the gray-scale plots, are preliminary. Much of this work is still in progress. Each star has its own character, but typically when one observes a diagonal pattern in the gray-scale plot of the CCF the time series analysis shows one dominant period and the power is greater in the line wings than in the line core. This suggests NRP as opposed to RM of a hot/cool spot. We intend to produce models for the profile variations in the next step of our study.

L. Balona: In η Cen, over 800 echelle observations show that the line profile variations do not show the striped characteristic of NRP but rather a complex pattern which repeats with the photometric period. Moreover, there is alternate excess emission and absorption at the limbs, indicating an equatorial gas cloud co-rotating with the star. In this particular star (an in some others) it is difficult to see how NRP can be responsible for these observations.

G. Peters: The CCF display for η Cen is more complex than for some stars, but one does faintly see the diagonal signatures that we attribute to NRP in the plot, the period from the time series investigation is consistent with the FUV/optical photometric periods, and furthermore the absorption bumps cross the line center very close to the times of maximum FUV flux. This is quite consistent with the NRP scenario. My major problem with accepting a rotation interpretation for η Cen is that the period of $\sim$0.6 days is significantly shorter than the range of rotation periods one would expect for the star adopting reasonable values for its radius and inclination.

M. Smith: (comment) NRP is only one mechanism for producing the striations you see in the cross-correlation of your *IUE* data. Co-rotating clouds which are dense enough to become optically thick even in the continuum can become in effect "local detached photospheres" and masquerade as low-order NRP in the line profiles through their absorptions of the true photospheric profile.