Photospheric Variability in *EUVE* Observations of β Canis Majoris (B1 II–III)

DAVID H. COHEN, JOSEPH J. MacFARLANE,
AND JOSEPH P. CASSINELLI

Department of Astronomy, University of Wisconsin at Madison,
475 No. Charter Street, Madison, Wisconsin, 53706, USA

The only pulsating early-type star observed by *EUVE*, the β Cephei variable β CMa, displays periodic variability in its Lyman continuum which is basically consistent with the long-known optical and UV variability. The amplitude of the primary pulsation component is significantly larger in the EUV than in the optical or UV. This is consistent with a temperature change being the explanation for the variability. It is notable that the pulsations have been detected in the Lyman continuum because this part of the spectrum is formed in a much higher layer of the photosphere than either the UV or optical continua.

1. β Canis Majoris

The brightest β Cephei variable, β CMa, lies in the region of unusually low column density known as the Canis Major Tunnel. Due partly to the lack of serious interstellar extinction and partly to its intrinsic brightness β CMa is the second brightest star in the *EUVE* long wavelength (LW) spectrometer. Variability has been observed in the optical since 1908 and in the UV over the past two decades. Three pulsation periods have consistently been identified in the optical data. The amplitudes (in the optical) and the periods are so similar that there is a strong beat phenomenon, with beat periods $B_{12} = 49.2$, $B_{13} = 5.4$, and $B_{23} = 4.9$ days.

The dominant period has an inverse amplitude-wavelength relationship that can be explained as a change in effective temperature. Beeckmans & Burger (1977) use the variability at 1810 Å to deduce the change in effective temperature of 180 ± 130 K for the first period and 180 ± 140 K for the second. It should be kept in mind that this temperature change occurs at a Rosseland optical depth of two-thirds. In contrast, the Lyman continuum is formed at a Rosseland optical depth of less than 0.01.

2. β Cephei Variables

The β Cephei variables lie in a small region of the HR diagram above the main sequence. All of the known β Cephei variables in our galaxy have spectral types in the range B0 to B3 and luminosity classes in the range IV to II. These stars show brightness, radial velocity, and line profile variability. The pulsations have generally small amplitudes ($\Delta m_v < 0.2$) and the pulsation periods are typically 4 to 8 hours. Many are "beat" Cepheis with two or more slightly different periods. Increasing variability toward shorter wavelengths indicates that pulsations cause primarily a temperature change (Sterken & Jerzykiewicz 1993).

The β Cephei instability strip includes the end of the core H-burning phase and may extend through shell H-burning. No period-luminosity relationship has been proven. The exact pulsation mechanism has only recently been identified. It is a pure kappa-mechanism due to a bump in the iron opacity near 200,000 K that is now included in the OPAL opacity calculations (Kiriakidis, El Eid, & Glatzel 1992; Moskalik & Dziembowski 1992; Dziembowski & Pamyatnykh 1993).

S. Bowyer and R. F. Malina (eds.), Astrophysics in the Extreme Ultraviolet, 389–394.

TABLE 1. Stellar Data

D (pc)	206
m_v	1.97
Sp. Type	B1 II–III
$T_{\rm eff}$ (K)	23250
$\log g$	3.5
$N_{\rm H}$ (cm^{-2})	2×10^{18}

TABLE 2. Optical and UV Pulsation Periods

	Optical (Shobbrook 1973)	UV (Beeckmans & Burger 1977)
P_1 (days)	$0.2512985 \pm .0000003$	0.2512985
P_2 (days)	$0.25003 \pm .00004$	0.2500225
P_3 (days)	$0.23904 \pm .00004$	

TABLE 3. Best-Fit Light Curve Model Parameters

	Best Model			Range (low:high)		
	Period (d)	Δmag	ΔT_b (K)	Period (d)	Δmag	ΔT_b (K)
P_1	0.251065	0.084	108	0.2509955 : 0.2511318	0.059 : 0.108	76 : 139
P_2	0.249952	0.020	26	0.249609 : 0.250082	0.011 : 0.046	14 : 59
P_3	0.239035	0.022	28	0.23904	0.022	28

3. Observations

The primary goal of this study is to determine if the pulsations propagate to the very high atmospheric layers where the Lyman continuum is formed and to accurately measure the temperature change in those layers. To do this we use two, long-duration ($\sim$ 50 ks and $\sim$ 100 ks) *EUVE* LW spectrometer observations made in the first two cycles of *EUVE* general observing. The elapsed observing times for the two observations are 3 and 6 days, and they are separated by 70 days.

We first analyzed the light curve composed of the source counts on the interval 504 Å to 700 Å (see Figure 1). The hypothesis of a constant source was ruled out at a very high significance level. The power spectrum revealed a highly significant signal near 6 hours. But the known periods could not be resolved; the data set is not long enough. We then fit models to the light curve. We used the same multiple sinusoidal model that Beeckmans & Burger (1977) used to fit the UV data. Two periods gave a better fit to the data than a single period, and three improved the fit still more. We used the $\Delta\chi^2$ criterion of Lampton, Bowyer, & Margon (1976) to define the 68% confidence limits of parameter space. The best fit and limits are shown in Table 3. The parameters describing the third period were held constant for the error analysis because of the insensitivity of the parameter values describing the first and second periods to the values of those describing the third.

Comparing our results to those from the UV data we see that the trend of increasing variability with decreasing wavelength for the first period continues into the EUV, but that the second period has a relatively constant amplitude (as it does within the UV). We find a temperature change consistent with that found by Beeckmans & Burger (1977) but better constrained. The folded light curve (on P_1) is shown in Figure 2. The contributions from P_2 and P_3 have been subtracted from the data. The fact that the temperature change in the EUV is consistent with that in the UV indicates that the

https://doi.org/10.1017/S0252921100036277 Published online by Cambridge University Press

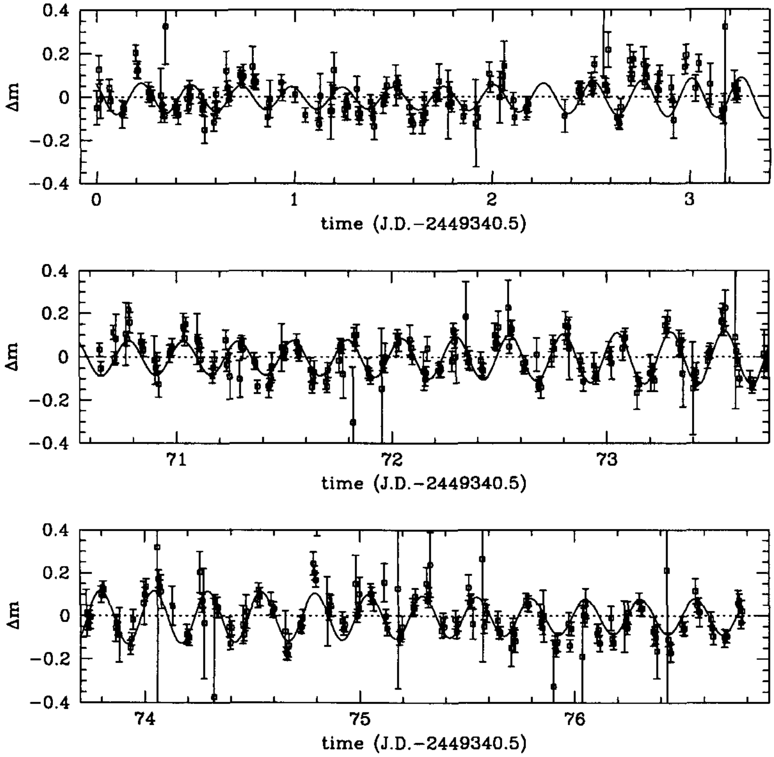

FIGURE 1. The observed light curve with the best-fit three-component sinusoidal model. Note in that the amplitude of the model changes throughout the observation. This is evidence of the beat period(s).

pulsations are not significantly damped as they traverse more than six density scale heights in the photosphere.

Even the best three-component fit is less than ideal. To investigate the cause, we subjected the residuals of the best fit to the same analysis procedure we applied to the data. We found no significant residual power in any one or several frequencies in the power spectrum of the residuals. It seems that either there is some stochastic variability superimposed on the periodic variability or there are significant systematic errors which we have not been able to account for.

In order to investigate the wavelength dependence of the variability within the *EUVE* bandpass we first created two separate light curves—one restricted to counts below 550 Å and the other to counts above 550 Å. We fit these with the same model that was fit to the original light curve. Not only is the light variation larger in the short wavelength band, but the temperature variation is marginally greater in the shorter wavelength band. Because of the $\sim \lambda^3$ dependence of the continuum opacity, the shorter wavelengths in the Lyman continuum are formed at lower layers. Since there is marginally less variability in

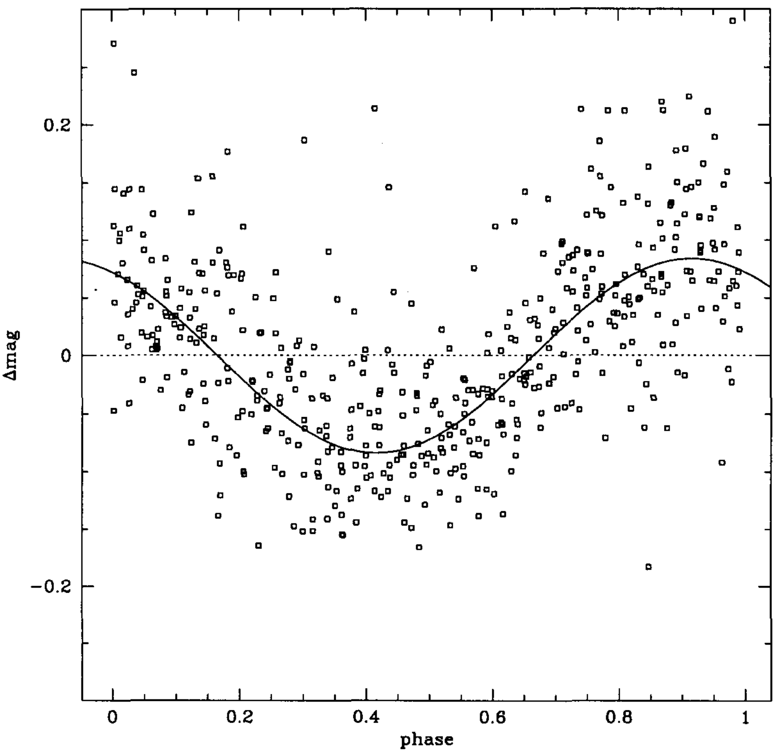

FIGURE 2. The observed light curve, with the best-fit model for periods 2 and 3 subtracted, folded on the best-fit primary period.

the radiation coming from the higher layers of the Lyman continuum formation zone, it is possible that we are seeing pulsations begin to dissipate within the upper photosphere.

Another method to examine the wavelength dependence of the variability is to weight the counts in the data by the sine of the phase of the principle period. The resulting spectrum represents the difference between the spectrum in the high and low states (see Figure 3). There is no way to account for the second and third periods in this analysis however, so the temperature derived from fitting the phase-weighted spectrum will not be as accurate as that derived from the light curve. However the high resolution may provide some information about the lines. Although the data are noisy, it appears that some of the high ion lines such as O V 630 and O IV 554 do not vary as much as the surrounding continuum. This could also be understood in terms of the dissipation of pulsations because the line centers are formed in significantly higher layers than is the surrounding continuum.

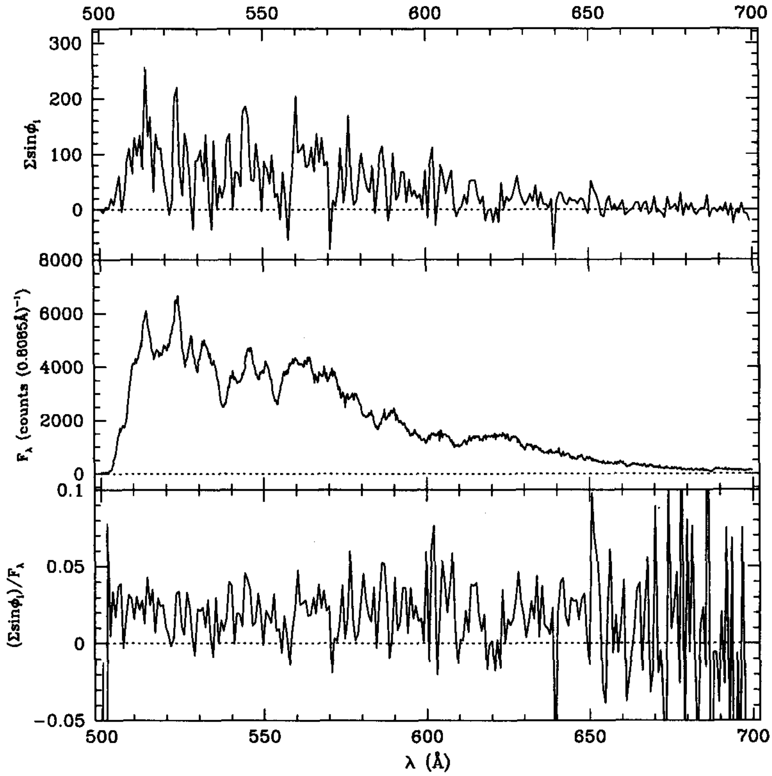

FIGURE 3. The phase-weighted spectrum is shown in the top panel along with the full spectrum in the middle panel and, in the third panel, the ratio of the two is shown.

4. Conclusions

Periodic variability, consistent with β Cephei pulsations are observed in the bright B giant β CMa. The three periods seen in the optical are detected in the *EUVE* data. The change in temperature associated with the primary period is consistent with that seen in the UV, but better constrained (108 ± 31 K). This indicates that the pulsations propagate relatively intact from $\tau_R \approx 2/3$ to $\tau_R \approx 0.01$.

We wish to thank Chris Johns for the use of his period analysis software, and Keivan Stassun and Ken Nordsieck for fruitful discussions.

REFERENCES

BEECKMANS, F., & BURGER, M. 1977, A&A, 61, 815

DZIEMBOWSKI, W., & PAMYATNYKH, A. A. 1993, MNRAS, 264, 204

KIRIAKIDIS, M., EL, EID, M. F., & GLATZEL, W. 1992, MNRAS, 225, 1p

LAMPTON, M., MARGON, B., BOWYER, S. 1976, ApJ, 208, 177

MOSKALIK, P., & DZIEMBOWSKI, W. 1992, A&A, 256, L5

SHOBBROOK, R. R. 1973, MNRAS, 101, 257

STERKEN, C., & JERZYKIEWICZ, M. 1993, β Cephei stars from a photometric point of view, Space Science Reviews, 62, 95