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Research Study of β Cephei Variable Stars Using Data from OAO-2

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ABSTRACT

Photometric data from the Wisconsin Experiment package on OAO-2 were obtained for six β Cephei variable stars. The data were reduced according to the procedure described in the OAO 2/Wisconsin Experiment Package (WEP) Photometer Users Guide (NSSDC 74-02). For two of the stars, δ Cet and γ Peg, there were enough data points to form reliable composite light curves at seven or eight ultraviolet wavelengths. The light curves are well represented by sine waves in phase with the blue light curve for each star. The amplitude of the light variation increases as one goes to shorter wavelengths.

For the remaining stars (θ Oph, ϵ Cen, κ Sco, and λ Sco), mean magnitudes and light ranges were obtained at several ultraviolet wavelengths. The mean, de-reddened ultraviolet colors of all the observed stars were compared with the mean values for standard stars computed by Bottemiller. No significant differences were found.

An attempt to derive a temperature scale from a comparison of the observed ultraviolet colors with Kurucz models was unsuccessful. An empirical temperature scale will be derived when ultraviolet photometry is available for all the stars observed by Code, David, Bless and Hanbury Brown.

I. Data and Reduction Procedure

The following photometric data from the Wisconsin Experiment Package on OAO-2 were obtained from the Space Astronomy Laboratory of the University of Wisconsin: δ Cet, 159 usable frames of photmetry; γ Peg, 157 frames; θ Oph, 58 frames; ε Cen, 51 frames; κ Sco, 47 frames; and λ Sco, 52 frames. The observations were reduced by hand, in order to avoid possible errors in the number of digital overflows, such as are sometimes introduced in the computer reduction program. The reduction procedure was as described in the OAO 2/Wisconsin Experiment Package (WEP) Photometer Users Guide (NSSDC 74-02). In particular, dark current and calibration source variations, sky background, filter degradation, and photometer "dead time" were all taken into account. For a moderately bright star, 11 frames of photometry yield 1 or 2 independent data points at each of 8 ultraviolet wavelengths; for the brightest stars, the photometers are saturated at some of these wavelengths. Averages were <u>not</u> taken between independent data points obtained on the same orbit, in order to preserve information concerning time variations in the brightness of the star.

II. Light Variations

A. δ Ceti

This star was observed by OAO-2 on 19-20 July 1971, 29 July 1971, and 7-8 August 1972 (UT). None of the photometers was saturated at any wavelength; it was possible to obtain useful data at 4250, 3320, 2980, 2460, 1910, 1550, 1430, and 1330 Å. Observing times were recorded to the nearest second and converted to Julian day numbers, and phases were computed using the period and epoch of maximum blue light given by Jerzykiewicz (1971). It was later found necessary to correct these phases by +.05; this correction represents the accumulated error in the year between the determination of the epoch and the present observations, and is not unusual in a star of such a short period. It was also necessary to make some small zero point corrections to the 1972 magnitudes, in order to make their mean agree with that of the 1971 observations. These corrections were +.02 mag for 4250 Å; 0 for 3320 Å and 2990 Å; -.01 mag for 2460 Å; +.02 mag for 1910 Å; +.04 mag for 1550 Å; +.16 mag for 1430 Å; and +.02 mag for 1330 Å. They presumably represent uncertainties in the filter degradation curves.

At each wavelength, a sine curve was then fitted to the observed magnitudes and phases by the least-squares method. The formal probable error of the amplitude and mean value of the sine curve was typically .001 mag, except at the three shortest wavelengths where it was .003 to .004 mag. The mean magnitudes and light ranges found for δ Cet in this way at eight wavelengths are listed in Table 1. The light curves themselves are shown in Figure 1, where filled circles denote observations made on 29 July 1971, open circles denote observations made on 19-20 July 1971, and crosses denote observations made on 7-8 August 1972.

It is evident from Figure 1 that all the ultraviolet light curves are in phase with the blue light curve, and that the light amplitude increases as the wavelength decreases. Quantitatively, Table 1 shows that the light amplitude increases from .026 mag at 4250 Å (approximately equal to the B and V amplitudes found by Jerzykiewicz 1971) to .100 mag at 1330 Å. This effect is to be expected, since early B stars emit the majority of their radiation in the ultraviolet (see Watson 1971).

B. γ Pegasi

This star was observed on 21-27 January 1972 and on 23-24 January 1973 (UT). The S1 photometer was saturated at 4250 Å, but usable data were obtained at the seven other wavelengths listed above. After conversion of the observing times to Julian day numbers, phases were computed using the period of Jerzykiewicz (1970) and the epoch of maximum radial velocity given by Sandberg and McNamara (1960). A phase difference of 0.25 was subtracted from the radial velocity phase to obtain the blue light phase, but it was also necessary to correct the computed blue light phases by -.15. This fairly large correction is due partly to the uncertainty of the phase difference, and partly to the fact that more than ten years elapsed between the determination of the epoch, and the present observations.

The 1973 data were taken within a 12 hour period and gave smooth light variations in phase with the blue light curve (filled circles in Figure 2). The 1972 data, however, showed a very large scatter, possibly (but not necessarily) due to the fact that the observations were spaced out over almost a week. The data from photometer S3 proved to be usable with a suitable zero-point correction (+.01 mag for 2460 Å and +.03 mag for 1910 Å; crosses in Figure 2) but the S1 and S4 data had to be discarded. Unfortunately, this made it impossible to construct light curves at 1430 Å and 1330 Å, since these wavelengths were observed only once in 1973. The sine curves fitted to the 1973 data at the five longer wavelengths are shown in Figure 2, and their mean values and amplitudes are listed in Table 1. For 1430 and 1330 Å, Table 1 lists only the single measurement made in 1973.

Unlike δ Cet, γ Peg shows no significant increase of light amplitude with decreasing wavelength except at 1550 Å. However, this star has a much smaller light amplitude than δ Cet at all wavelengths, and since there are fewer accurate observations, the amplitude variation might well have been missed.

C. θ Ophiuchi

This star was observed on 27-28 February and 2-3 March 1971. The phases corresponding to the observing times were computed using the period of Van Hoof and Blaauw (1958) and the epoch of maximum light of Watson (1971). Data were obtained at the same 7 wavelengths as for γ Peg, but onlya few observations (6 in most cases) were made at each wavelength. Since these showed a large scatter, no attempt was made to fit sine curves by the least-squares method. Instead, curves were drawn through the points by inspection, and mean magnitudes and light ranges were estimated from these curves. These mean magnitudes and light ranges are listed in Table 1. The light variations in θ Oph appear to be very similar to those in γ Peg. There is a slight tendency for larger amplitudes to occur at the shortest wavelengths.

D. Three New Variables

Shobbrook (1972) and Shobbrook and Lomb (1972) identified ϵ Cen, κ Sco, and λ Sco as β Cephei variables. All of these stars show multiple periods, making it difficult to phase observations taken over several cycles. No epochs of maximum light are given. The ranges in blue light are very small.

OAO-2 observations of ϵ Cen were made on 4-6 February 1971; κ Sco, 20 February and 4 March 1971; and λ Sco, 17 and 21 February and 3 and 5 March 1971. All three stars are so bright that only measurements at the shortest wavelengths are usable. For the reasons given above, no attempt was made to phase the observations or to draw light curves, but mean magnitudes were computed and light ranges estimated directly from the data. These are listed in Table 1. The results are compatible with the assumption that these three stars are true β Cephei variables having the periods and blue light ranges stated by their discoverers.

III. De-reddened Colors

Bottemiller (1975) presents mean relationships between the de-reddened ultraviolet colors $(m_\lambda - V)_o$ and $(B-V)_o$ for standard early-type stars, as well as extinction ratios $(m_\lambda - V)/E(B-V)$ which facilitate the correction of the observed ultraviolet colors for reddening. Using these extinction ratios we computed de-reddened colors for δ Cet, γ Peg, and θ Oph at all the available ultraviolet wavelengths. E(B-V) was computed by the Q-method for γ Peg and δ Cet, using the UBV photometry of Jerzykiewicz (1970, 1971). For θ Oph, an intrinsic color of $(B-V)_o = -.25$ was assumed, based on the spectral type. The observed de-reddened colors are listed in Table 2.

Table 2 also shows, in parentheses, ultraviolet colors computed from Bottemiller's mean $(m_\lambda - V)_o$ vs $(B-V)_o$ relations. The standard errors σ for these relations are rather large. For δ Cet and γ Peg, the residuals between observed and calculated colors are rarely greater than 1.0 σ (exceptions: 1910Å for δ Cet, 1.1σ; 1430Å for δ Cet, 1.3σ; 1910Å for γ Peg, 1.8σ). The observed colors for θ Oph are systematically redder by 1.5-2.5σ than the computed colors. However, Bottemiller points out that the stars in the Scorpio-Centaurus association may not follow exactly the same extinction curve as the other stars in his sample, and the discrepancies for θ Oph can probably be attributed to errors in the reddening correction.

We conclude that there is no strong evidence for significant color differences between β Cephei variables and "normal" B stars. In particular, the present observations do not support the suggestion of Lesh and Aizenman (1973) that β Cephei stars may be slightly bluer than non-variable stars. (This suggestion was made, however, particularly with regard to stars of luminosity class III; δ Cet, γ Peg and θ Oph are all class IV stars.).

IV. The Temperature Scale

Although some progress has recently been made in our understanding of the instability mechanism of β Cephei stars, the connection between theory and observation is still tenuous. Aizenman, Cox and Lesh (1975) have shown that the basic mechanism may be an unstable non-radial g-mode, which has a large amplitude at the point where nuclear driving by the hydrogen-burning shell source is large. However, the g-mode has too long a period to be the observed mode in β Cephei stars; rather, it must drive a shorter-period mode through non-linear coupling. According to Lesh and Aizenman (1974), the observed mode is probably a radial harmonic or non-radial p-mode.

One method of distinguishing among possible observed modes is to compute the velocity-to-light amplitude ratio. This quantity is defined observationally as

$$\frac{24}{17}\ \frac{P}{2\pi R}\ \frac{2K}{(\Delta V + \Delta BC)},$$

where 24/17 is the limb-darkening factor, P is the period, R is the mean radius, 2K is the radial-velocity amplitude, ΔBC is the variation of the bolometric correction. From the theoretical point of view, the amplitude ratio is equivalent to the ratio of the change in radius to the change in luminosity, which can be calculated for a given mode from a quasi-adiabatic pulsation analysis of the model star. For a radial fundamental mode, the theoretical value of this quantity is 0.1; for a radial first harmonic mode, 0.05; and for a radial second harmonic mode, 0.03.

In obtaining the observed value of the amplitude ratio for a given star, the adopted temperature scale is critical. The temperature enters strongly in the computation of ΔBC (which is a larger term than ΔV for β Cephei stars!) and R (through the formula $L = 4\pi R^2 T_e^4$). Temperature changes in β Cephei stars are very small. Preliminary calculations using UBV photometry have indicated that for γ Peg and δ Cet, the temperature change produced by pulsation is only 300-400°K. However, the temperature scale from UBV photometry does not lead to a value of the amplitude ratio that is accurate enough to distinguish among the various possible pulsation modes.

Because of the large amount of energy emitted by B stars in the ultraviolet, ultraviolet colors are much steeper functions of temperature than colors at longer wavelengths. One goal of the present project is therefore to use the OAO-2 photometry to set up an accurate temperature scale for β Cephei stars. This can then be used in conjunction with the very accurate bolometric corrections obtained by Code et al. (1974) to compute the amplitude ratios. (The temperature scale of Code et al. is not usable in its present form because it is tied to $(B-V)_o$, a quantity which is very difficult to observe with any accuracy.)

Our first attempt to derive an ultraviolet temperature scale consisted of forming the colors $(m_\lambda - m_{3320})_o$ for six wavelengths in γ Peg and δ Cet, and comparing these with the predicted colors in a grid of model atmospheres provided by Kurucz (private communication). This attempt was unsuccessful, in the sense that no unique temperature could be obtained by using all six colors. Apparently the statistically blanketed models, which coincide with the real stellar spectrum only on the average, can lead to spuriously high or low slopes in different wavelength intervals.

Although it would undoubtedly be possible to improve the agreement by a suitable smoothing of the models, a more promising approach is to adapt the temperature scale of Code et al. (1974) by tieing it to observed ultraviolet colors of the standard stars. A particularly good color to use would be $(m_{1550} - m_{2460})$, which requires no reddening correction. But if photometry at 2460Å is not available for many of the bright standard stars, $(m_{1550} - V)_o$ is another possibility. The completion of this phase of our project awaits the reduction of OAO-2 photometry for the standard stars of Code et al. We expect to receive this photometric data from Wisconsin within a few weeks.

V. Publications and Acknowledgments

This work was presented at the 145th meeting of the American Astronomical Society in Bloomington, Indiana, and is abstracted in the Bulletin of the American Astronomical Society 7, 252, 1975. It is now being prepared for publication and will be submitted to the Astrophysical Journal as a paper in the series, "Ultraviolet Photometry from the Orbiting Astronomical Observatory." Reprints will be sent to NASA as soon as they are available.

It is a pleasure to acknowledge the excellent cooperation of the staff of the Space Astronomy Laboratory and the Department of Astronomy of the University of Wisconsin, especially Prof. A. D. Code and Dr. A. V. Holm. I also wish to thank Dr. Blair Savage for many useful conversations, and Dr. R. Kurucz for sending me his model atmospheres prior to publication.

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Table 1

Mean Ultraviolet Magnitudes and Light Ranges of β Cephei Variables

Star | λ(Å)	4250	3320	2980	2460	1910	1550	1430	1330
δ Cet	3.178	2.547	2.285	1.771	1.171	0.619	0.429	0.082
	.026	.051	.058	.063	.073	.085	.086	.100
γ Peg		1.320	1.073	0.528	-0.079	-0.674	- 0.99	- 1.27
		.032	.038	.037	.035	.052		
θ Oph		1.78	1.50	0.97	0.34	- 0.23	- 0.48	- 0.76
		.04	.04	.04	.04	.06	.06	.05
ε Cen					- 0.83	- 1.44		
					.03	.06		
κ Sco					- 0.61	- 1.22	- 1.48	- 1.75
					.03	.03	.03	.04
λ Sco						- 1.96	- 2.32	- 2.62
						.05	.08	.06

Table 2

Observed and Calculated De-reddened Ultraviolet

Colors of β Cephei Stars

Star | λ(Å)	4250	3320	2980	2460	1910	1550	1430	1330
δ Cet	-0.934 (-0.942)	-1.593 (-1.587)	-1.871 (-1.859)	-2.446 (-2.459)	-3.057 (-3.141)	-3.598 (-3.694)	-3.7[illegible] (-3.971)	-4.160 (-4.127)
γ Peg		-1.540 (-1.580)	-1.796 (-1.851)	-2.379 (-2.448)	-2.992 (-3.129)	-3.581 (-3.681)	-3.902 (-3.957)	-4.192 (-4.112)
θ Oph		-1.50 (-1.58)	-1.78 (-1.88)	-2.31 (-2.49)	-2.94 (-3.13)	-3.51 (-3.69)	-3.76 (-3.95)	-4.04 (-4.25)

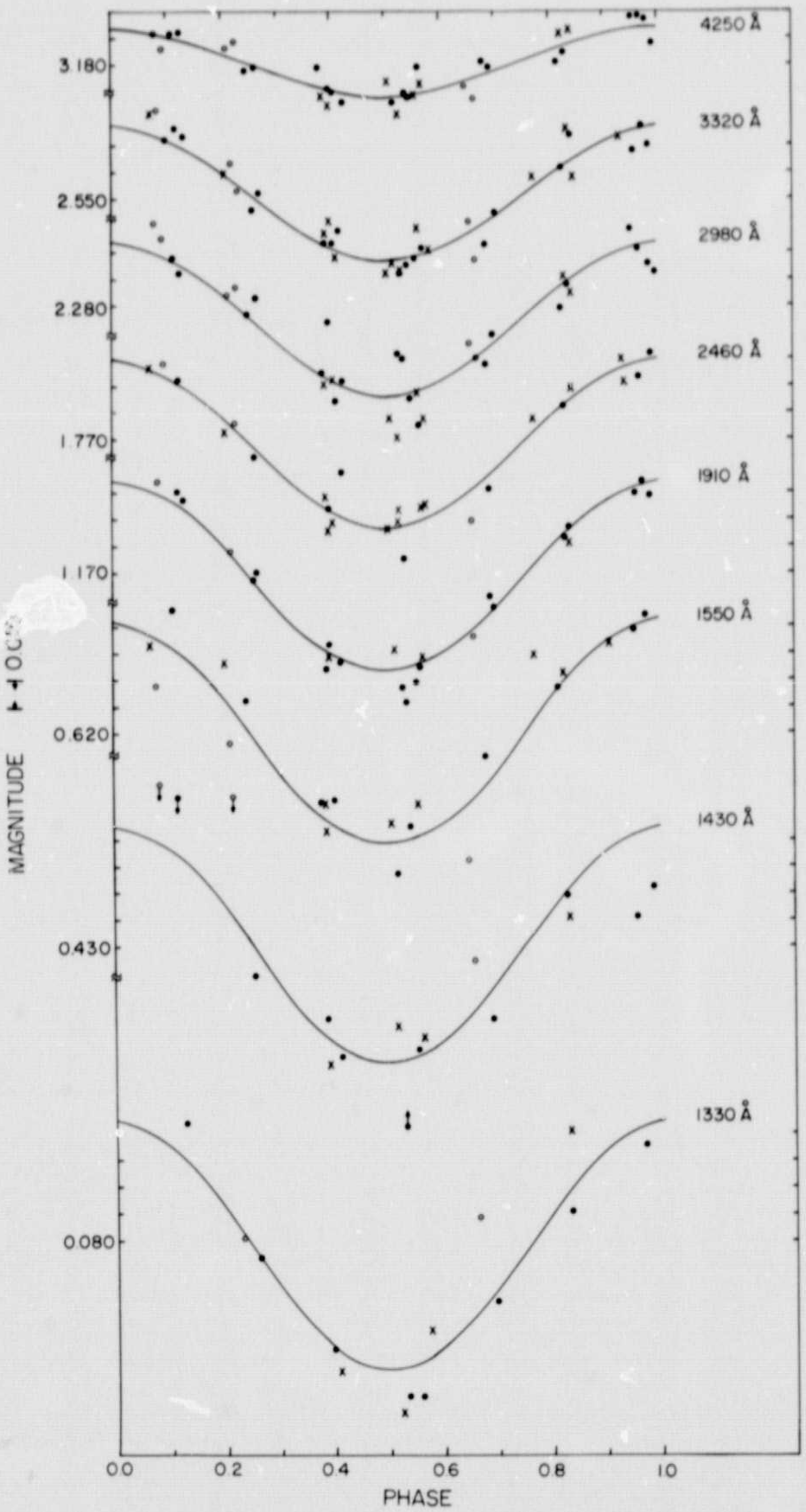

Figure 1: Ultraviolet light curves for δ Ceti.

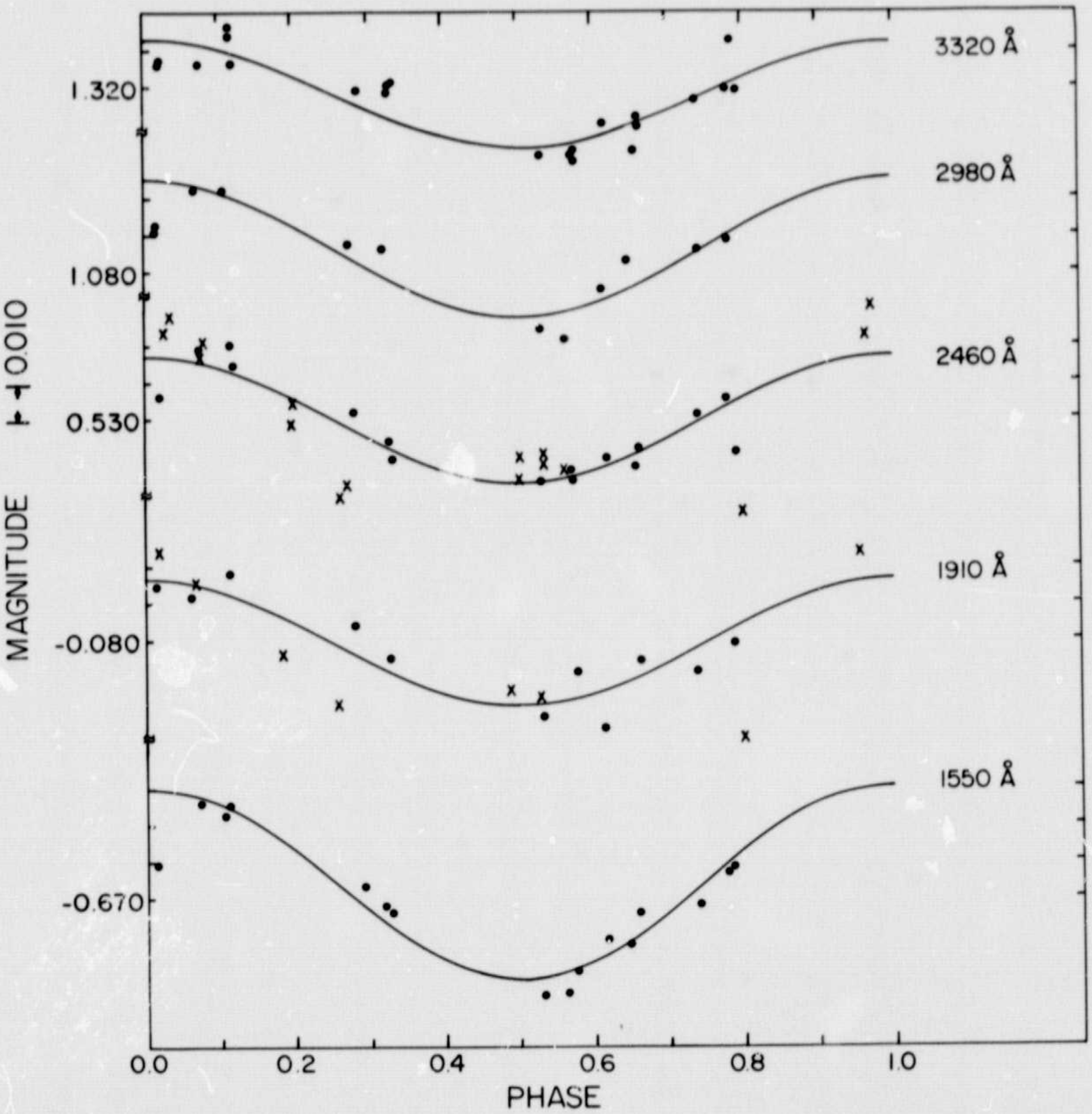

Figure 2: Ultraviolet light curves for γ Pegasi.