

Interpretation of OAO-2 ultraviolet light curves of β Doradus

James L. Hutchinson

Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, Colorado 80302

Stephen J. Hill

Department of Astronomy and Astrophysics, Michigan State University, East Lansing, Michigan 48824

Charles F. Lillie

Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, Colorado 80302

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OA0-2 observations of β Doradus are presented. A simple hydrodynamical model containing atmospheric shock waves describes the origin of the bumps of these UV light curves.

INTRODUCTION

THE variable β Doradus is one of a small number of classical cepheids exhibiting a bump in the visual light curve and velocity curve near the phase of maximum light. The observations of β Dor presented in this paper indicate additional bumps in ultraviolet light curves. Pulsation computations by Christy (1966) and others have suggested that the single bumps on the visual light and velocity curves can be interpreted as originating from a reflection of a pressure-density compression wave from the dense stellar core. Refinements in computational techniques, notably finer mass zoning and radiative transport treatment of the atmosphere (e.g., Bendt and Davis 1971; Davis 1975) have shown the bump to be a permanent feature in the computed light and velocity curves. In this paper we present middle-ultraviolet light curves and other evidence to indicate that the additional bumps, as seen in these curves, have their origin in shock-wave phenomenon in the upper atmosphere of the cepheid. This interpretation is supported by the observations of Ca II in emission at certain phases (Gratton 1953) and by the measurements of the H α radial velocities (Bell and Rodgers 1967). Also, variation of the surface gravity with phase has suggested that running waves are consistent with model-atmosphere calculations (Parsons 1971).

The observations of β Dor have an interesting history. Due to its fourth-magnitude brightness, β Dor would seem to be a likely candidate for pulsational investigations of bumps, but its relative inaccessibility in the southern hemisphere has severely hampered obtaining sufficient observational data. Indeed, until 1927 β Dor was thought to be nonvariable in light. As reported in the collection of meridian photometer observations, Bailey (1903) found it necessary to obtain four times the number of separate observations because of the observed "scatter" of a quarter of a magnitude. However, he did not conclude that β Dor was variable. Applegate (1927) published a detailed radial velocity curve but did not acknowledge that β Dor was variable in light. Shapley and Walton (1927) used new measurements and those of Bailey to discover that β Dor was a classical cepheid. Since 1930 only four photometric studies have been made and of these only the *UBV*

observations of Irwin (1961) are complete enough to adequately describe the light curves.

The ultraviolet photometry of β Dor as obtained by the Wisconsin Experiment Package (WEP) on OAO-2 is presented in Sec. I. Section II contains a description of the simple, piston-driven, spherical hydrodynamical model of the atmosphere of β Dor. Section III contains a comparison of the results of this model with the ultraviolet and other observations. Conclusions are presented in Sec. IV.

I. OBSERVATIONS

The principal observational material used in this work was obtained by the WEP in two separate intervals during September 1969 and July 1970. The instrumentation has been described by Code *et al.* (1970). Data obtained in the first observing run are of slightly lower quality due to the presence of increased noise from the South Atlantic Anomaly. All data were reduced according to the method established by Doherty (1972) for late-type stars; no corrections for field stars were necessary. All known instrumental effects were removed including filter degradation and relative filter sensitivities.

The ultraviolet OAO-2 data are listed in Table I and plotted in Fig. 1; open symbols represent the first observing run; filled symbols, the second run. Phasing was obtained using a period of 9.8420 days. The maximum expected photometric errors are estimated by the sum of the scatter due to counting statistics and the peak-to-peak variations in the dark and sky counts. These errors are approximately the size of the symbols used with the exception of the 1910-Å data, where the two error bars shown in Fig. 1 give the maximum expected error at maximum and minimum light. The magnitude of the 1910-Å errors arises principally from uncertainties in sky background determinations. The few points at 2980 Å that lie significantly above the general run of the other data are spurious, due to some unknown, occasional instability in the 2980-Å photometer.

The increase in light curve amplitude toward shorter wavelengths continues through the ultraviolet to an amplitude of about 2^m.75 at 1910 Å. This wavelength-

TABLE I. β Dor OAO magnitudes corrected for sky, extinction, and instrumental sensitivity.

JD 2440000	Phase	$\lambda 4250$	$\lambda 3320$	$\lambda 2980$	$\lambda 2460$	$\lambda 1910$
476.742	0.491	-2.32	-0.94	-0.24	1.69	2.69
477.240	0.542	-2.29	-0.95	-0.22	1.50	2.91
478.145	0.634	-2.40	-1.18	-0.50	1.22	2.70
478.870	0.677	-2.63	-1.45	-0.84	0.72	2.01
479.120	0.733	-2.76	-1.63	-1.29	0.41	1.82
479.677	0.789	-2.88	-1.74	-1.27	0.29	1.74
480.164	0.839	-3.02	-1.83	-1.33	0.12	1.40
480.649	0.888	-3.06	-1.86	-1.35	0.12	1.19
532.310	0.137	-3.13	-1.97	-1.51	0.12	1.66
533.076	0.215	-2.97	-1.73	-1.17	0.54	2.22
533.146	0.222	-2.96	-1.73	-1.17	0.58	2.16
533.215	0.229	-2.92	-1.69	-1.16	0.62	2.10
533.285	0.236	-2.93	-1.70	-1.15	0.66	2.16
533.355	0.243	-2.92	-1.68	-1.10	0.71	2.29
535.234	0.434	-2.41	-1.06	-0.36	1.55	3.15
535.721	0.484	-2.35	-0.98	-0.27	1.66	3.13
536.278	0.540	-2.28	-0.93	-0.21	1.68	2.89
536.766	0.590	-2.35	-1.02	-0.32	1.50	2.99
537.253	0.639	-2.47	-1.21	-1.50	1.15	2.09
537.740	0.689	-2.66	-1.49	-0.85	0.70	2.07
537.814	0.696	-2.71	-1.54	-0.94	0.63	2.13
538.228	0.738	-2.80	-1.63	-1.04	0.39	1.88
788.263	0.145	-3.09	-1.98	-1.46	0.18	1.28
788.837	0.201	-3.00	-1.85	-1.21	0.46	1.71
788.897	0.208	-2.98	-1.81	-1.17	...	1.76
788.037	0.222	-2.95	-1.77	-1.14	0.59	1.76
780.105	0.229	-2.92	-1.75	-1.11	0.65	1.71
789.176	0.237	-2.91	-1.73	-1.10	0.66	1.71
789.392	0.259	-2.85	-1.66	-0.99	0.82	2.60
789.732	0.293	-2.77	-1.55	-0.87	...	2.76
789.801	0.300	-2.75	-1.53	-0.85	1.03	2.50
789.874	0.308	-2.74	-1.50	-0.80	1.08	2.75
790.082	0.329	-2.67	-1.43	-0.83	1.18	2.66
790.367	0.358	-2.60	-1.34	-0.68	1.33	2.55
791.054	0.427	-2.44	-1.12	-0.41	1.63	2.94
791.749	0.498	-2.32	-0.95	-0.25	1.75	3.99
791.817	0.505	-2.33	-0.99	-0.23	1.78	4.56
792.031	0.527	-2.30	-0.98	-0.21	1.76	2.96
792.314	0.555	-2.29	-0.99	-0.31	1.70	...
792.722	0.597	-2.35	-1.06	-0.41	1.54	4.51
792.791	0.604	-2.36	-1.08	-0.40	1.49	3.14
793.007	0.626	-2.41	-1.15	-0.44	1.34	2.46
793.695	0.696	-2.67	-1.51	-0.90	0.69	2.33
793.766	0.703	-2.69	-1.55	-0.95	0.72	1.85
793.840	0.711	-2.71	-1.58	-1.04	0.52	1.66
794.050	0.732	-2.77	-1.65	-1.07	0.41	1.48
794.405	0.768	-2.83	-1.72	-1.21	0.31	1.35
794.741	0.802	-2.92	-1.80	-1.29	0.25	1.38
795.024	0.831	-2.98	-1.88	-1.33	0.13	1.12
795.378	0.867	-3.04	-1.93	-1.40	0.06	0.91
795.714	0.901	-3.06	-1.93	-1.39	0.09	1.29
795.859	0.916	-3.06	-1.94	-1.39	0.09	1.24
796.068	0.937	-3.08	-1.96	-1.44	0.04	1.06
796.353	0.966	-3.16	-2.05	-1.66	-0.11	1.01
796.424	0.973	-3.18	-2.08	-1.77	...	...
796.689	0.000	-3.28	-2.20	-1.74	-0.32	0.59
796.760	0.007	-3.30	-2.22	-1.76	-0.37	...
797.044	0.036	-3.33	-2.25	-1.76	-0.39	...
797.327	0.065	-3.26	-2.19	-1.66	...	...
797.398	0.072	-3.23	-2.16	-1.63	...	0.96
797.660	0.099	-3.16	-2.07	-1.53	...	...
797.733	0.106	-3.14	-2.05	-1.50	0.00	1.03
797.804	0.113	-3.13	-2.03	-1.48	0.04	1.27

dependent amplitude is quite linear with inverse wavelength (Hutchinson 1975).

At ultraviolet wavelengths, additional features develop on the rising branch of the light curve. We shall denote the bump at phase 0.75 as B1, that at phase 0.85 as B2, and the bump near phase 0.0 as B3. These

bumps are much larger than the maximum expected errors and appear in the light curves of several photometers; it is unlikely that they are instrumentally induced.

There is a shoulder, B4, which is visible in the 3320- and 4250-Å curves. This feature is more prominent in the visual light curve (Fig. 2) from the data of Mitchell *et al.* (1964). There is yet another feature at phase 0.3 in the *I* curve of the *UBVGRI* results of Breckinridge and Kron (1963).

Colors show essentially the same behavior as their parent light curves. The smoothed (2460-3320) and (2460-*V*) colors are plotted in Fig. 3 against the smoothed (*B-V*) color (using the *UBV* data of Mitchell *et al.* 1964). Superimposed upon a narrow, open color-color loop (solid line) are two thin, very blue arms (dashed lines) indicative of rapid, short-lived heating in the atmosphere. A third arm (not shown)

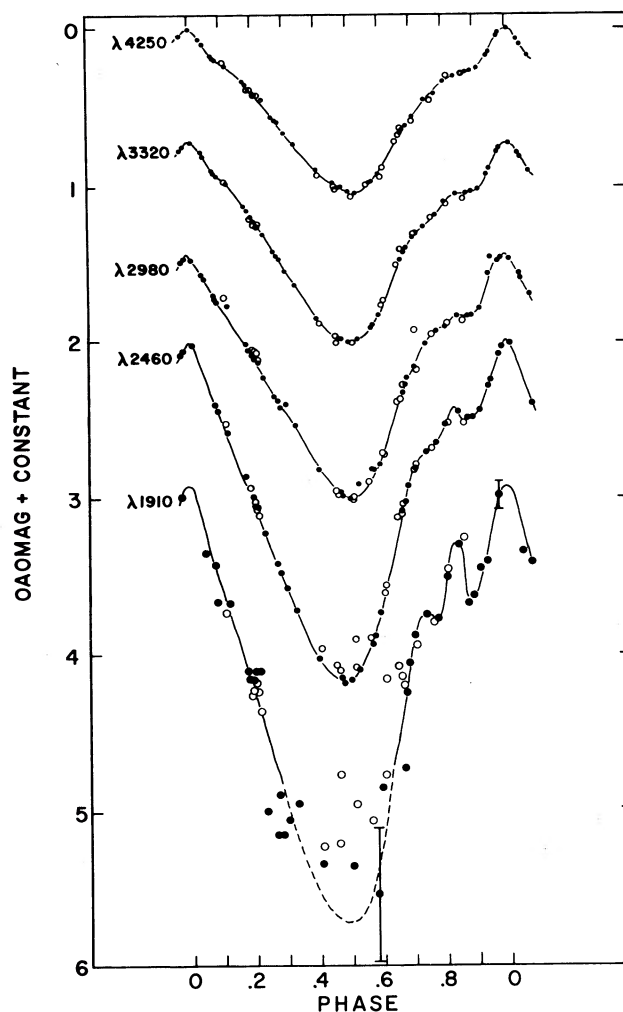


FIG. 1. Light curves of β Dor for five OAO-2 filters. Open symbols for observations in September 1969 and closed symbols for observations in July 1970. The expected photometric errors are approximately the size of the symbols used except at $\lambda 1910$ where the error bars shown apply at maximum and minimum light.

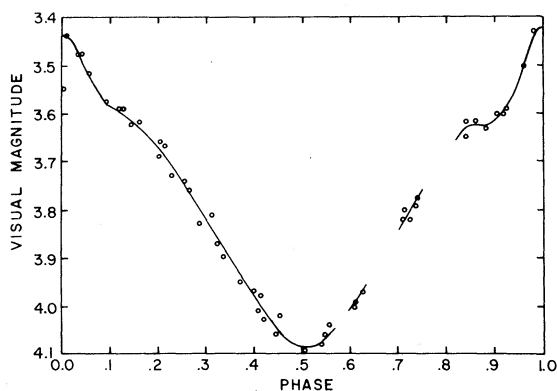


FIG. 2. Observed visual magnitude of β Dor. From Mitchell, Iriarte, Steinmetz, and Johnson (1964).

appears at phase 0.75 if the 1910-Å data are included. We show later that shocks generated by atmospheric motion can produce such behavior in the ultraviolet.

Figure 3 assumes $E_{B-V} = 0.09$. This is an average of the results of Parsons and Bouw (1971) and Breckinridge and Kron (1963). This value is also supported by the fact that β Dor is separated by only six degrees from the large Magellanic Cloud for which $E_{B-V} = 0.08$ (Gascoigne 1969). We suggest that the higher determinations of E_{B-V} for β Dor as determined by Gascoigne and Eggen (1957) and of Walraven *et al.* (1958) are in error. We believe that the color-color diagram and the evidence of a shock-wave contribution at maximum light (described below) modifies the assumption of

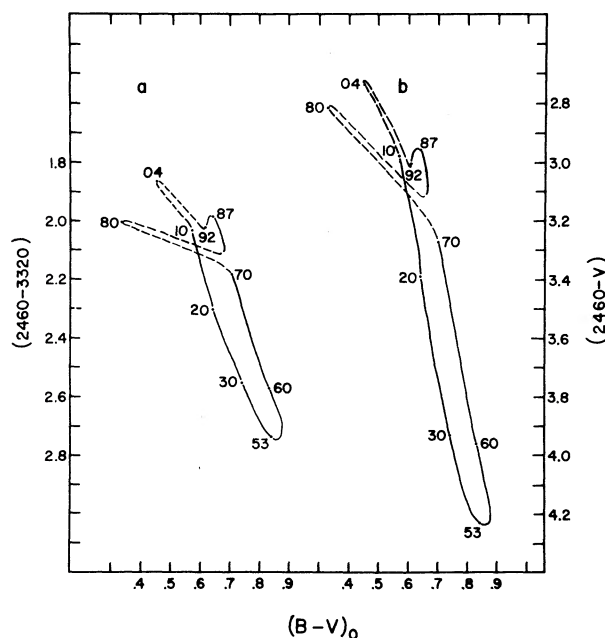


FIG. 3. The (a) (2450-3320) and (b) (2460-V) color-color behavior of β Dor shows an elongated loop with thin blue arms at the phases of shock bumps. These color-color curves are derived from smoothed color curves. The numbers give the phase in units of 0.01.

normal colors at maximum light which gave the higher value for E_{B-V} .

There has been a renewed interest in considerations of stability of the periods of variable stars prompted by evolutionary calculations. Schmidt (1971), for example, found the stability of the period of Y Oph to be 1 part in 10^4 . For β Dor the ephemeris,

$$\text{JD}(\text{max light}) = \text{JD}2435206.44 + 9.84200E,$$

from the Russian *General Catalog of Variable Stars* (Kukarkin *et al.* 1969) was used to reduce all observed times of maximum to form an (O-C) plot of phase difference versus Julian date. The resulting straight-line correlation in the phase of observed maximum indicates that no period change greater than about one part in 10^6 has occurred, and the ephemeris used is accurate to this order. (Figures 1 and 2 indicate that phases of maximum light are independent of effective wavelengths.)

II. NUMERICAL METHOD

The numerical model is based upon the usual mass and momentum equations approximated by their finite-difference form with the inclusion of quadratic, artificial-viscosity pressure term. The model is spherically symmetric. The finite-difference formulation is described by Richtmyer and Morton (1967). To speed execution for numerous models, the isothermal approximation is used. This is justified by the rapid postshock cooling as found by Whitney and Skalafuris (1963). It is also justified by the numerical hydrodynamical calculation for an RR Lyrae atmosphere and calculations of the resulting shock waves (Hill 1972). These calculations explicitly included the effects of radiative losses.

The atmosphere is driven by a spherical piston. Both the velocity and location of the piston are specified as a function of time. Parson's (1971) summary table of the observed velocities is used. These weak line velocities are assumed to originate at a constant-mass depth. The inability to precisely know the location of a given optical depth is necessitated by the isothermal approximation. It is believed that the use of a constant-depth piston is the greatest source of possible error in this analysis. This difficulty is again mentioned in the next section. The mass depth for the placement of the piston was determined from the β Dor-type model atmospheres by Parsons (1969).

TABLE II. Characteristics of β Dor model.

Period	8.5035×10^5 sec
Average radius	4.32×10^{12} cm
Outer-mass depth	1×10^{-7} gm/cm ²
Inner-mass depth	3×10^1 gm/cm ²
Mass ratio $[M(I)/M(I+1)]$	1.2
Gravitational acceleration	
at average radius	4×10^4
Temperature of isothermal atmosphere	6000°K

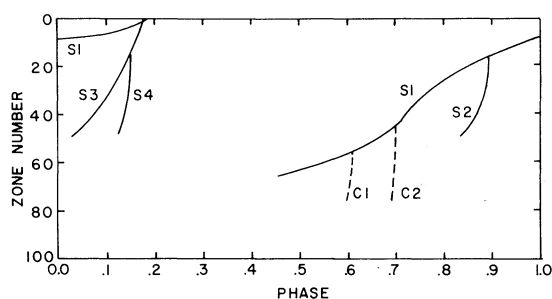


FIG. 4. Location of shock front in β Dor model. The compression events are denoted by the dashed lines.

III. RESULTS AND COMPARISON WITH THE OBSERVATIONS

The characteristics of the β Dor model are listed in Table II. Figure 4 illustrates the location of the shock waves and compression waves in the atmosphere. For reference, Fig. 5 illustrates the piston velocity which is used for this model. In the model there is one main shock wave (S1) which is enhanced by the strong phases of compression (C1 and C2) and by three more "feeder" shock waves (S2, S3, and S4). (For the purposes of this paper, a shock wave is termed such only when it exhibits a velocity discontinuity greater than the sound speed.) The main shock wave is produced at phase 0.5 as a result of the deceleration of the piston. The main shock is then strengthened by the strong compression events: The first is associated with the phase of zero outward acceleration and the second is associated with the phase of zero velocity. These changes in the acceleration of the piston are in opposition to the lower-density preshock material, which,

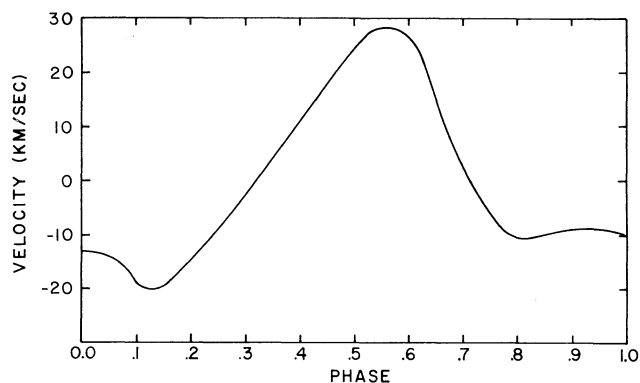


FIG. 5. Radial velocity curve used in β Dor model. From Parsons (1971).

because of the low-pressure gradients, is still accelerating inward. Figure 6 shows the preshock zones in their accelerated return to the shock front. In this figure the compression due to each shock is seen. Figure 7 indicates the rapid increase in the velocity discontinuity due to the two compression events. At phase 0.85, the first outward maximum velocity of the piston, a second shock (S2) is produced. It quickly merges with the main shock. The infall of the postshock material behind the main shock (S1) in combination with the outward velocity of the piston, produces the third shock (S3). The piston reaches a second maximum velocity at phase 0.1 and creates the fourth shock (S4). Shortly after the shocks combine to strengthen the main shock (S1), the main shock leaves the upper zone of the model.

Figure 8 illustrates the radiative flux expected from the shock waves in this model. This was calculated from

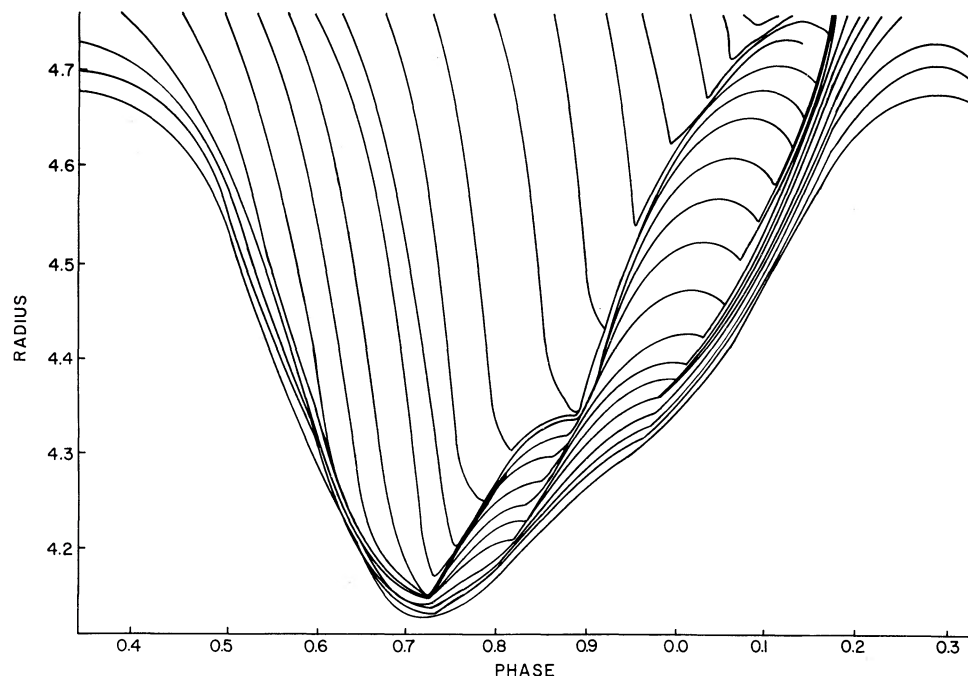


FIG. 6. Relative position of zones of constant-mass depth in the β Dor model.

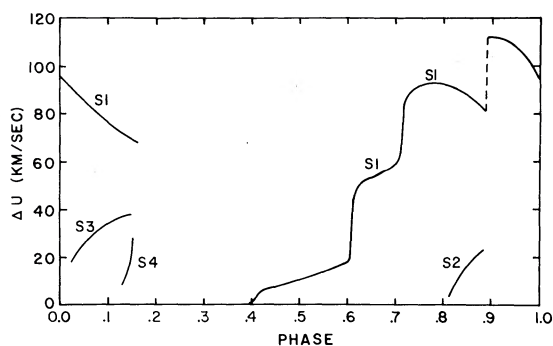


FIG. 7. Velocity discontinuity (ΔU) across shock front as obtained from the model.

the relationship for the flux (Hill 1972),

$$F = \rho (\Delta U)^3 / 2,$$

where ρ is the preshock density, and ΔU is the velocity discontinuity of the shock. Figure 8 indicates that there are maximum contributions to the radiative flux by the shock at phases 0.64, 0.72, 0.85, 0.04, and 0.13. Because hydrogen is ionized by velocity discontinuities greater than 50 km/sec we would not expect ultraviolet radiation from the main shock (S1) before a phase of 0.7, or from the fourth shock (S4) at any phase. The remaining contributions at 0.72, 0.85, and 0.04 are then identified with B1, B2, and B3 in Fig. 1. The energy contribution at phase 0.13 may in fact manifest itself as the very suggestive shoulder at phase 0.15 in Fig. 2 of the photometric visual observations of Mitchell *et al.* (1964).

The phases of the production of the initial weak shocks could be in error. Particularly susceptible to error is the phase of the production of S1 (seen at phase 0.4). From the range 0.4–0.7 the opacity is increasing due to the compressional increase in the density and the increase in the effective temperature. Thus, the optical depth scale will move out through mass during those phases. In the real star, the location of constant-mass depth will have a greater inward acceleration during those phases than the radial velocity observations would indicate. (The velocity observations were

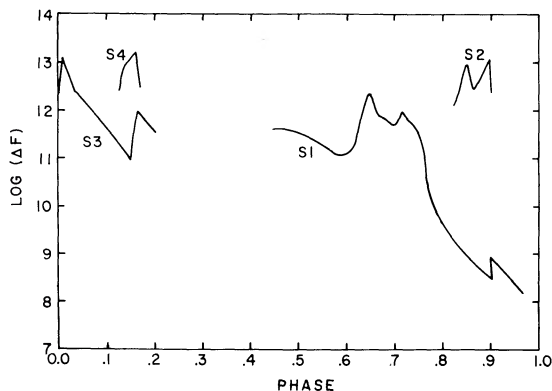


FIG. 8. Radiative energy losses (ΔF , in ergs/cm²/sec) as obtained from the model.

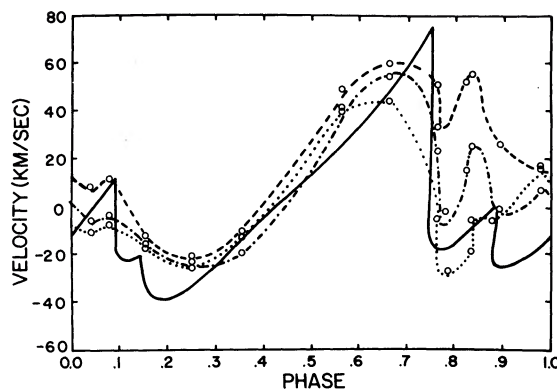


FIG. 9. H velocity curves for β Dor. The continuous line is obtained from the model. The dashed line is from Bell and Rodgers (1967) who used the location of minimum intensity. The other two lines are obtained from the $H\alpha$ line profiles by Bell and Rodgers. The dashed line with dots used the location of the optical center of mass of the lines in the range $\lambda = \pm 4 \text{ \AA}$. The dotted line is derived from the line center of the line as measured at a midpoint at a depth of one-third the line depth.

used as if they originated from a constant-mass depth.) This greater inward acceleration in the real star should retard the formation of the weak shock to a later phase than is indicated in Fig. 7. Also, the "hard" nature of the piston, in not allowing the motions in the atmosphere to alter the position of the piston, would tend to produce a shock which is too early in its phase.

The solid curve in Fig. 9 illustrates a velocity for constant-mass depth appropriate for the formation of the $H\alpha$ line. The mass depth for the formation of the $H\alpha$ line was obtained from Preston (1969). Observational curves are presented for comparison. They all originate from the same line profiles for β Dor as given by Bell and Rodgers (1967). The poorest fit is derived if the velocities are measured by using the point of minimum intensity in the cores of the lines. An improved fit is obtained by using the optical center of gravity of the absorption line. This is in keeping with the results of van Hoof and Deurinck (1952). They concluded for similarly asymmetric absorption lines (of Eta Aquilae) that the 24/17 correction factor is only applicable when used with the position of the optical center of gravity of the absorption line. The figure also presents the resultant velocities where the line center is chosen to be the midpoint of a depth of one-third the line depth. This was chosen as a representative depth in the line which an observer might select in measuring the apparent center of the absorption core. It is very revealing to observe that the velocity discrepancy due to the different methods of measurement indicated in Fig. 9 ranges from only 2 km/sec to almost 80 km/sec approximately one-half a period later. This lack of a constant correction factor for the strong lines was emphasized by Teske (1961).

In the light of the uncertainties in the interpretation of the radial velocity observations, it is encouraging to note that the phases and the relative shock strengths

are not in contradiction with suitably corrected observations. In fact, the comparison throws doubts on the use of uncorrected measurements made at the bottom of the central core of the strong absorption lines.

IV. CONCLUSIONS

The observations of the Wisconsin Experiment Package on OAO-2 reveal small bumps on the rising branch of the light curve of β Dor which were not previously observed in the visible light curves. A simple hydrodynamical calculation indicates that these UV flux bumps are due to atmospheric shock waves. The hydrodynamical model is also consistent with observed radial velocity curves.

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