THE LIGHT AND VELOCITY CURVE BUMPS FOR BW VULPECULAE

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I. INTRODUCTION

BW Vulpeculae (HD 199140) is a well known Beta Cephei star, with several unusual characteristics. It possesses the largest amplitude in both light and radial velocity variations, of any star in this classification. The most outstanding feature of the observations is a standstill or bump, on the light curve, accompanied by doubled lines in the radial velocity observations. In this paper, we have attempted to explain these phenomena with two different models. Firstly, the resonance mechanism, from Simon and Schmidt, and secondly, a non-linear calculation.

II. RESONANCE MECHANISM

The resonance mechanism was first advanced by Simon and Schmidt (1976). It can be used to explain the "bumps" on the light curves of Cepheid and BL Herculis variables. (Hodson and Cox (1980) and King et al. (1980). While the nature of the standstill found in BW Vul is quantitatively different from that of the Cepheids, a study was undertaken to determine whether a resonance was at work in the star.

The presence of a resonance is denoted by the following relationship

$$0.47 \lesssim \Pi_2/\Pi_0 \lesssim 0.53$$

where Π_2 = period of second radial overtone mode

Π_0 = period of the radial fundamental mode.

From Cepheid calculations (Stobie 1969a,b), the above ratio is also correlated with the position of the bump with respect to the maximum of the light curve. The relationship is:

Space Science Reviews **27** (1980) 337–343. 0038–6308/80/0273–337 $01.05.

$\Pi_2/\Pi_0 < 0.50$ bump on rising light

$\Pi_2/\Pi_0 > 0.50$ bump on falling light

$\Pi_2/\Pi_0 = 0.50$ bump at maximum

We would therefore expect a model from BW Vul to have a period ratio slightly less than one half.

Models spanning the region of the HR diagram where the Beta Cephei variables are found were constructed using a stellar modeling code developed at LASL. A linear, non-adiabatic stability analysis, using Castor's code (1971), was performed on the models. This yielded periods and eigenfunctions for the radial fundamental and first two radial overtone pulsational modes.

Several evolutionary states of these massive stars were studied. The end of the hydrogen exhausted core contraction phase is used as being the most appropriate. This gave the closest fit to the period of BW Vul for a radial fundamental mode. An assumed mass-luminosity relationahip is given in Table 1. Values were obtained from Iben (1965a,b.) and Lamb, Iben and Howard (1976). Depletion of core hydrogen due to nuclear burning was calculated from the same references, and a representative graph of hydrogen abundance is given in figure 1. (11 $M_\odot$)

Table 1

Mass (Solar Units)	Log $L/L_\odot$
10	4.12
11	4.25
12	4.37
13	4.48
14	4.58
15	4.66
17	4.81
19	4.93

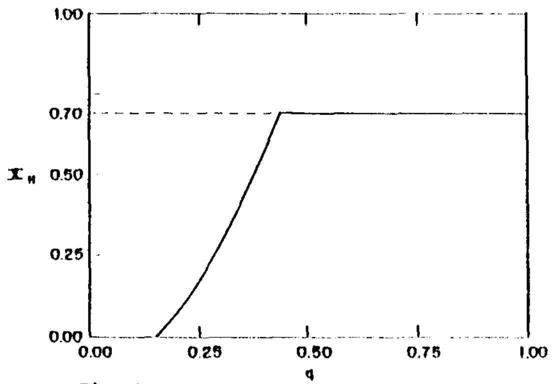

Fig. 1 Hydrogen Abundance vs. Mass Fraction

When compared with earlier calculations (Lesh and Aizenman 1974), our periods are shorter by a noticable amount. The length of the radial fundamental mode was considered by Lesh and Aizenman to discount it's presence in Beta Cepheis. Our calculations show that the radial fundamental is not eliminated in the lower luminosity stars, but is still unlikely in those stars of higher luminosity.

This shortening of the period is directly related to the mass concentration of the star. According to Ledoux and Walraven (1958) a more centrally condensed star has a shorter period. Decreasing the hydrogen content of the core will increase the mean molecular weight, increasing

https://doi.org/10.1017/S0252921100081732 Published online by Cambridge University Press

the density of the core. This results in a more centrally condensed star and therefore a shorter fundamental period. (See Cox and Giuli, 1968, p.764).

The results of the calculations are summarized in figure 2. Straight lines represent lines of constant period, and are labeled by the appropriate radial fundamental period, in days. The two curves are lines of constant period ratio for Π_2/Π_0. The crosses are observed points (Beeckmans and Burger, 1977, Jakate, 1979, 1980, Lesh and Aizenman, 1974, 1978.).

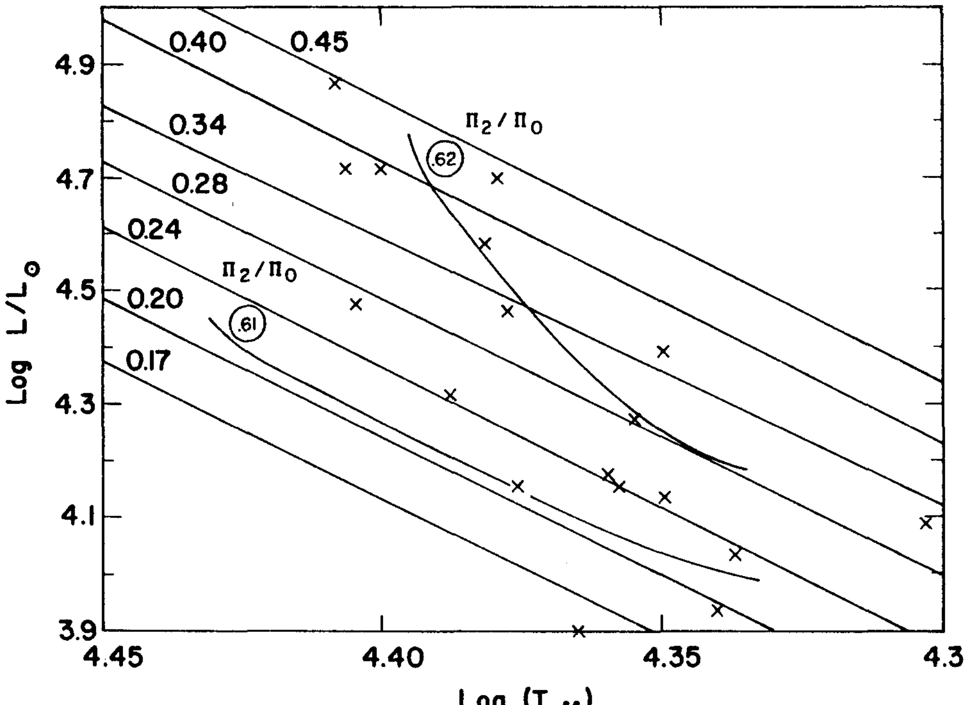

Fig. 2 Theoretical H-R Diagram

As the period ratios are nowhere near the value of one half, the resonance mechanism is clearly not responsible for the structure of BW Vul's light curve.

III. NON-LINEAR CALCULATIONS

When our first hypothesis failed to explain the bump, a second one was tried. Using a non-linear, Lagrangian, radiation, hydrodynamic code at LASL, a radial fundamental eigenfunction was driven at amplitudes suitable for BW Vul. Details of the model are Table 2. The theoretical amplitude was chosen from a formula by Campos and Smith (1980).

$$A_T = \frac{4}{3} \; K \left(\frac{10}{V_R}\right)^{0.06}$$

with A_T = theoretical radial velocity amplitude = 100 Km/sec

K = observed radial velocity amplitude = 80 Km/sec (Lane & McAlary, 1980)

V_R = rotational velocity = 38 Km/sec (Watson, 1972)

The results can be seen in figure 3, 4, and 5. There is a bump on the radial velocity curve at the proper phase. The radius dependence agrees well with that of Goldberg et al. (1976). However, the amplitude is far too large,

$$2K = 320 \text{ Km/sec}$$

as compared with an observed amplitude of

$$2K = 160 \text{ Km/sec}$$

The original theoretical amplitude was increased due to the application of the Stellingwerf SPS method to obtain a full amplitude oscillation. The initial Newton-Raphson corrections boost the amplitude to twice it's original value. The bump is a consequence of the rapid increase in the amplitude that resulted. Models that did not experience this corrective boost did not show the bump feature. As BW Vul experienced a similar "burst" in 1947 (Eggen 1948), this does not seem an unreasonable explanation for the bump. Although an explanation for the bump may be given, there is no driving in this model, so a true full amplitude pulsation will not be found. Further work will be done to see if the bump's existence can be explained more fully.

IV. CONCLUSIONS

We have attempted to model "bumps" in the light and radial velocity curves of the Beta Cephei star BW Vulpeculae. Two mechanisms, a resonance phenomena and non-linear pulsations, were investigated. The resonance condition was clearly not fulfilled, the calculated period ratio being approximately 0.60, where a value of 0.50 ± 0.03 is required for resonance. In the non-linear calculation, the bump appears, with the correct phase, but was found at an amplitude that is too large. Further, the light curve does not show any bump-like feature. The cause of the bump is the large spurious boost given the star's velocity field by the solution methods.

The calculated periods of the stellar models are shorter than those of previous calculations, enhancing the possibility that these stars pulsate in a radial fundamental mode.

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Table 2. Model For BW Vulpeculae

Mass	Radius	Luminosity	T_{eff}	π_0(d)	π_2/π_0
$11M_\odot$	$7.1R_\odot$	$17795L_\odot$	25120K	0.203	0.61

Envelope Composition: $X = 0.70$ $Y = 0.28$ $Z = 0.02$

Convection was not included in the Non-Linear Model.

The core is convective but we included only the envelope of the star, as this gave the desired fine zoning in the atmosphere.

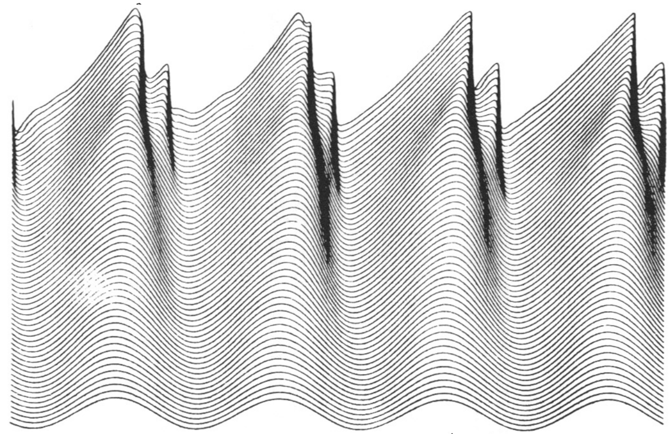

Fig. 4 Radial Velocity vs Time (6.99×10^4sec)
V(cm/sec) Ib=-4.76×10^4,4.78×10^4 ob=-1.87×10^7,2.16×10^7

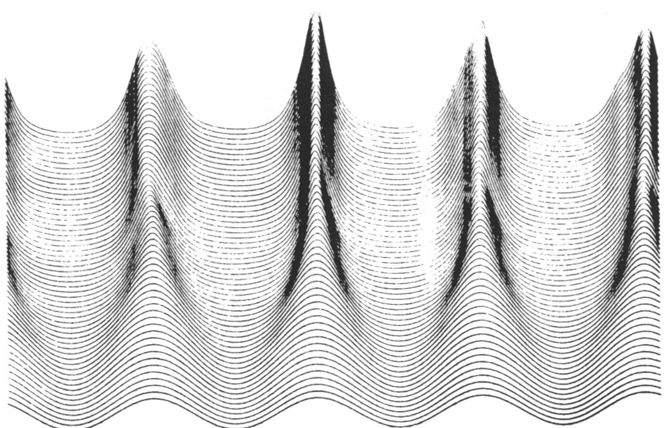

Fig.3 Radiative Luminosity vs Time (6.99×10^4sec)
L(erg/sec) ib=6.92×10^{37} 6.96×10^{37} ob=2.12×10^{37},2.63×10^{38}
bw vul non-linear $11.00M_\odot$ 25120K $17795L_\odot$ f 60 zones

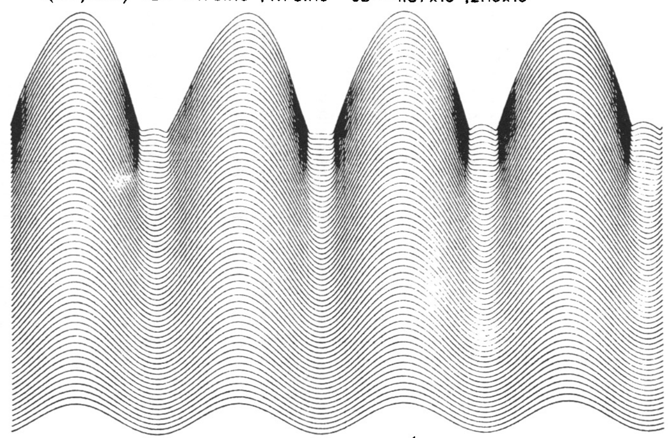

Fig. 5 Radius vs Time (6.99×10^4sec)
R(cm) ib=1.09×10^{11},1.10×10^{11} ob=4.57×10^{11},5.37×10^{11}
bw vul non-linear $11.00M_\odot$ 25120K $17795L_\odot$ f 60 zones

https://doi.org/10.1017/S0252921100081732 Published online by Cambridge University Press

We would like to thank Stephen Hodson for his help on the computer. The computing facilities were provided by the Los Alamos Scientific Laboratory.

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DISCUSSION

SIMON: First I'd like to dissociate myself from the view that all bumps anywhere, everywhere are associated with resonances. Don't you miss some damping by only zoning 50% of the mass?

PESNELL: Not really. No. We had surface zoning and core convection problems in our early models with only 6% of the mass in the core like for the α Vir problems. In order to get 4-5 optically thin zones instead of only 2, we zoned only to the depth where the semiconvection zone is.

SIMON: By ignoring that central mass are you missing an important region of the star?

PESNELL: No. The pulsations decay no faster or slower than the case where we put in the core. It's stable anyway.

A. COX: The damping for α Vir at about the same period is not really deep, definitely cooler than 10^6 K.

DEUPREE: The reason we always give for why our luminosity curves are so terrible is that we cannot define the location of the hydrogen ionization zone accurately. Your temperature is so high here that you don't have that problem, and your luminosity curve ought to be pretty nice.

YOUNG: What was the amplitude of the radius extension?

PESNELL: About 10-15% of the star at a radial velocity amplitude of about 200 km/s.

BREGER: The previous speaker told us that we are not allowed to integrate radial velocity curves through the cycle. This is indeed a tricky observational problem. Could you comment?

PESNELL: Goldberg, et al. have published two radius histories, and we found good agreement, at least in shape, between our calculations and the strong line radius variations.

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