NON-RADIAL PULSATION MODELS OF THE H-ALPHA PROFILE IN BW VULPECULAE

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ABSTRACT

The profile of the Hydrogen alpha spectral line in the large-amplitude Beta Cephei star BW Vulpeculae was modeled in terms of a linear, non-radially moving, and rotating stellar atmosphere. The pulsation and rotation parameters were derived from fitting the radial velocity amplitude, and the best fit was obtained for ℓ=2, m=-2, i=90°, rotation velocity=120 km/sec, and pulsation amplitude=27 km/sec. When the line profiles are compared to this model, the fit is quite encouraging for most phases, but several discrepancies remain. At the time of writing, it is not clear whether these can be made to disappear by increasing the sophistication of the model, or whether a completely different physical model (e.g. radial) is necessary.

I. INTRODUCTION

It has been suggested that BW Vulpeculae is a non-radial pulsator by M. Smith (1977) with ℓ=2, m=-2, and by Kubiak (1978) with ℓ=2, m=-1, both based on the fitting of spectral line profiles. In contrast, Stamford and Watson (1978) found that the wavelength dependence of the photometric amplitude for this star was consistent with radial pulsation. With high quality profiles of the H-α line available from Young and Furenlid (1980), it is worthwhile to model the behavior of the profile variation to determine which of the above suggestions is supported by the observations.

II. MODELING TECHNIQUE

The H-α line profile is a particularly difficult one to model, as the core is formed in a non-LTE region, and the wings are very sensitive to the gas pressure. However, the relatively low dispersion of the observations (0.456 Å/pixel) makes this the only line broad enough to be resolved.

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The stellar disk was divided into about 4000 squares, and the local radial velocity in the line of sight of earth was computed, assuming linear, non-radial pulsation plus rotation. This velocity field is specified by the parameters ℓ and m (spherical harmonic indices), i (inclination of the rotation-pulsation axis to the line of sight), V_{rot} (the equatorial rotation velocity), V_p (pulsation amplitude), and ϕ (pulsation phase). For each point on the star's surface, the intensity as a function of wavelength at the local angle normal to the surface is found from a model stellar atmosphere generated by the ATLAS6 program (Kurucz, 1979). The intensity is then Doppler-shifted by the appropriate local radial velocity and accumulated. When all parts of the star's disk have been treated, the line is normalized, and can be directly compared to the observed profiles.

III. RESULTS

1. The case of ℓ=2, m=-1.

It was suggested by Kubiak (1978) that the most likely mode of pulsation for BW Vul was the ℓ=2, m=-1 non-radial mode with i =60°, V_{rot}=160 km/sec, and V_p varying (from cycle to cycle) between 24 and 80 km/sec. To test this hypothesis, the line profiles with these parameters (also V_p=50 km/sec) were generated and the radial velocity was determined by locating the wavelength of the deepest point in the profile. This was compared to the radial velocity curve based on the same criterion applied to the observed profiles. The result is shown in fig. 1--it can be seen the for no choice of V_p do the shape and amplitude simultaneously fit the observed radial velocities. On this basis, the ℓ=2, m=-1 non-radial mode was abandoned.

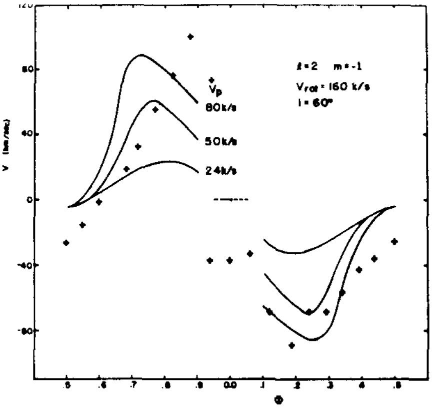

fig. 1-- Radial velocity curve for BW Vul based on position of maximum depth in the H-alpha line. Observed velocities (+) are compared to model predictions ℓ =2, m=-1 for three pulsation amplitudes.

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2. The case of ℓ=2, m=-2.

M. Smith (1977) was able to fit Si III line profiles at two phases for BW Vul with non-radial mode ℓ=2, m=-2, i=90°, V_{rot} 120 km/sec, and V_p 27 km/sec. Line profiles of H-α were computed and radial velocities (r.v.) found for these parameters as before (i.e. from the wavelength of the deepest point) and are shown in fig. 2 for three values of V_{rot}, and in fig. 3 for three values of V_p. The model which fits the amplitude of the r.v. curve is the same as that suggested by Smith, but there is a discrepancy in the shape of the curve. In particular, between phase (φ) 0.4 and 0.8, the observed r.v. lags by about 0.1 and the velocity of the stillstand (φ=0.95 to 0.05) is about 40 km/sec less than in the model (phase zero is defined at maximum light).

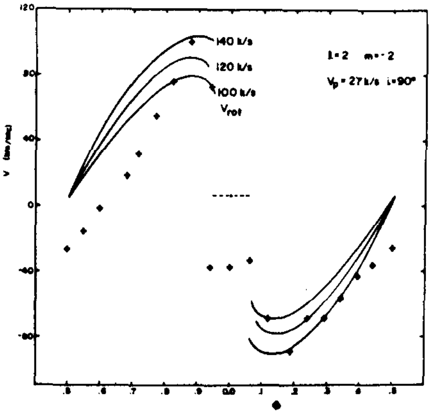

fig. 2-- same as fig. 1 but with ℓ=2, m=-2.

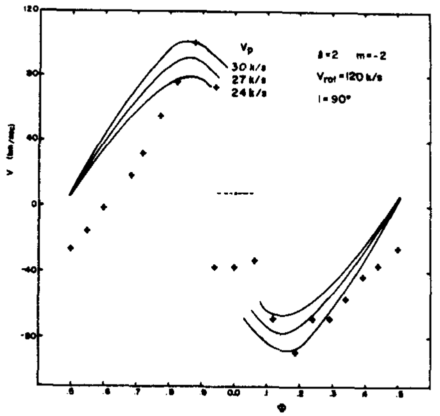

fig. 3--same as fig. 1 but with ℓ=2, m=-2.

The profiles of the observed H-α lines at six phases are plotted in fig. 4a, and are compared to those computed for the model V_{rot}=120 km/sec and V_{rot}=100 km/sec. At φ=0.0 the model gives a broad symmetrical line while the observed profile (#510, at the middle of stillstand) is considerably deeper, and (as noted earlier) is shifted 40 km/sec to the blue. At φ=0.3, the observed profile shape (#515) is matched well by the model, but is somewhat deeper. By φ=0.5, the observed profile (#519, on the rising branch of the r.v. curve) has a deep core and symmetrical shape, matched by the model, although the model line is not deep enough, and there is a r.v. difference of 30 km/sec. Profile #506 (at φ=0.77, just prior to maximum r.v.) is matched closely by the model with φ=0.70, but in the blue wing the model is too deep. By φ=0.88 (#508, at the maximum positive r.v.) the line is mimiced rather poorly by model φ=0.80-- the blue wing of the model is too deep, while the red wing is too shallow. At φ=0.94 (#509, beginning of stillstand), the observed line is very broad and shallow, with an absorption feature on the blue side of the core; the model which reproduces the absorption feature has φ=0.20, but it also fails to reproduce the broad red part of the line core.

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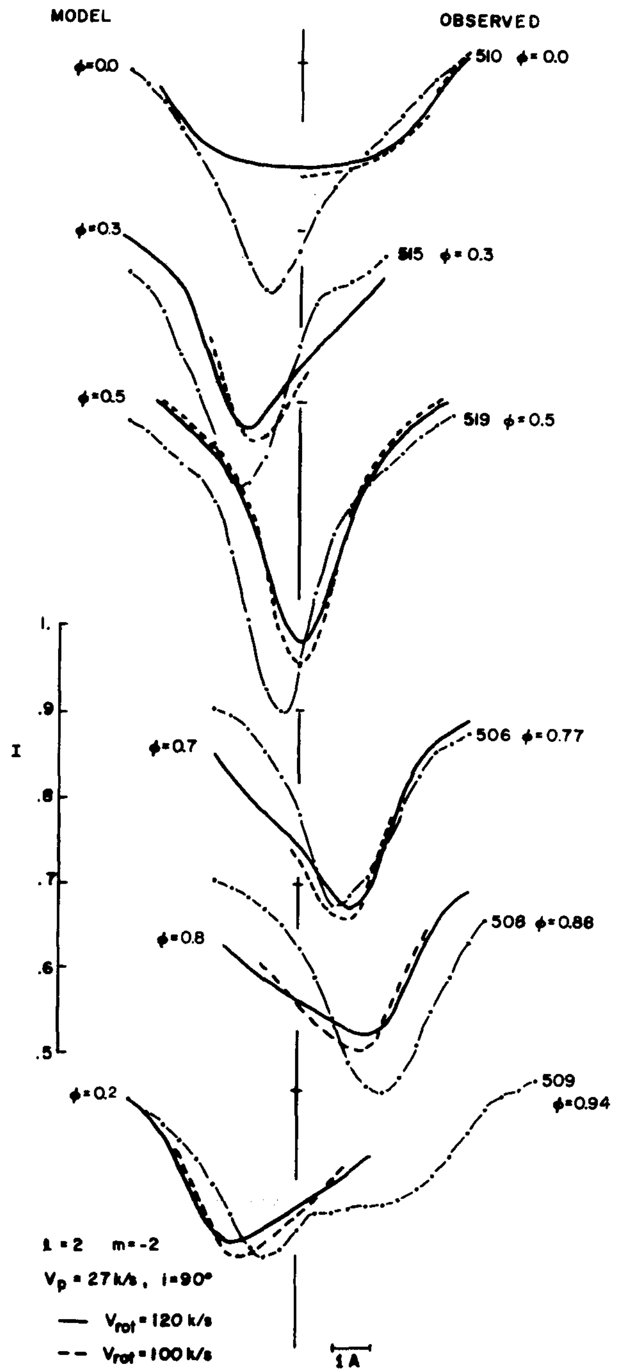

Fig. 4a--Comparison of the H-alpha profiles in BW Vul--the observed profiles (·—·—·) are displayed on the same scale as those generated by a non-radial model with V_{rot} =120 km/sec (———) and 100 km/sec (— — — —). The phase (φ) is given on the left for the model as derived from fig. 2; the phase given on the right is for the observed profile, where φ=0.0 corresponds to time of maximum light.

The two glaring discrepancies in this comparison are with observed line #510, which is deeper than the model at the same phase, and also line #509, which requires a much later model phase, and the model still fails to reproduce the red side of the line. One way to reconcile these problems is to use a model line profile with considerably different phase, as is done in fig. 4b. Here line #510 is compared to model φ=0.30; the deep, slightly asymmetrical profile is matched well in the blue, but is deeper in the red. The broad, shallow part of profile #509 is matched well by the model at φ=0.0, but the absorption feature observed in the blue is missing. This absorption feature grows rapidly with time from φ=0.94 to φ=0.0, and it is possible that the integration time ($\Delta\varphi$=0.05) has caused the profile to not exactly match any of the models presented here, which are instantaneous, i.e. no time averaging was done.

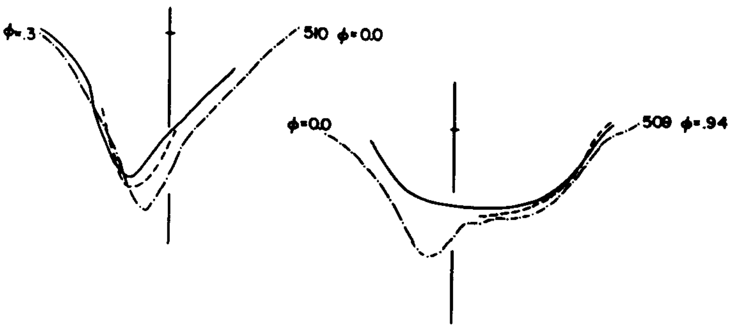

fig. 4b--Fit to the two discrepant line profiles after an adjustment of the model phase.

IV. DISCUSSION

The best attempt at understanding the profile variations in the H-α line of BW Vul come from the ℓ=2, m=-2, i=90°, V_{rot}=120 km/sec, V_p=27 km/sec. Several problems exist in the detailed comparison of the observed profiles with those predicted by this model, but the situation is eased as long as one relaxes a strict phase correspondence. The models computed here are completely linear, so that the phase is strictly sinusoidal, but non-linear effects would distort the time dependence from this simple form. It should be realized that this is true also of all radial and non-radial models--that any asymmetry in the radial velocity curve, or any phase discrepancy in the line profiles will never be matched by a linear model, and these must inevitably be explained in terms of non-linear effects.

Other discrepancies in the comparison of these line profiles might disappear with increased model sophistication, such as time averaging the models, allowing the temperature and pressure to vary with time and with angular position on the disk, or allowing for dynamic effects in the line source function. All of these complications are difficult to add to the model, but their effects may be important.

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Another approach to the problem will be attempted, that being to use a non-linear regression search of χ^2 space, to determine the value of model parameters which minimizes the difference between the observed and computed profiles. This would produce a run of various parameters through the cycle, some of which should remain constant (such as and V_{rot}). It would also allow a sensitivity estimate of the fit to each parameter.

V. CONCLUSIONS

The H-α line profile of BW Vul can be understood in terms of a relatively simple linear non-radial model, the fit being tantalizingly good, but still leaving several discrepancies. The velocity field in the model reproduces the observed line profile to better than 10% in fraction of continuum flux, and often somewhat less. In order to do this, the cycle phase at which agreement is attained must sometimes be changed from that of the linear model. Also the radial velocity of the stillstand is about 40 km/sec lower in the observations than in the model if the peak radial velocity is matched. It is suggested that both of these discrepancies are a result of non-linearities in the star's pulsation. It would be of interest to attempt to construct a radial pulsation model with a vertical velocity field in the line-forming region, to see if that assumption could also fit the profiles.

ACKNOWLEDGMENTS

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DISCUSSION

A. COX: Did you assume any radial mode?
ODELL: This is simply the amplitude for a nonradial mode.
M. SMITH: This star has one mode, one period.