FAST TIME-RESOLUTION SPECTROSCOPY OF BW VULPECULAE

Arthur Young
Department of Astronomy, San Diego State University

Ingemar Furenlid
Kitt Peak National Observatory[1]

ABSTRACT

An experimental Fairchild CCD-211 was placed in the 2.1-m coudé spectrograph at the Kitt Peak National Observatory and used to record an 87 Å spectral band centered on Hα. On the night of 1979 July 11 UT date, this system was used to observe continuously the extreme β Cephei variable BW Vulpeculae throughout one of its 4^h49^m cycles with an average exposure of 13 minutes per observation. A total of 18 observations was secured. The results show dramatic profile variations of Hα, including features not previously reported, and extreme variations of the C II λλ6578, 6582 lines, including variations of equivalent width. The fast time-resolution capability and the photometric linearity of the CCD have permitted the detection of subtle effects that have been missed by photographic observations and has led directly to important new interpretations of the complex atmospheric pulsations in this star, including effects of altered opacity on the formation of spectral lines and the suggestion of a helium-ionization heat engine as a mechanism for driving atmospheric pulsations.

INTRODUCTION

A perplexing and unique characteristic of the β Cephei variables is rapid and complex variation of spectral-line profiles. All investigators of these variable stars have recognized the importance of the profile variations, but studies of them with conventional photographic techniques suffer from severe limitations of time resolution and photometric linearity. The significant advances in detector technology in this past decade have permitted this problem to be investigated anew with emphasis on fast time resolution and photometric accuracy. The study reported here concerns the behavior of the Hα (λ6563) profile and of the adjacent lines of C II (λλ6578, 6582). The star BW Vulpeculae (HD 199140; V = 6.4 mag) was selected as the first β Cep star to be studied, because it is known to exhibit the most extreme variability of light, radial velocity, and line profiles.

Space Science Reviews 27 (1980) 329–335. 0038–6308/80/0273–329 $01.05.

OBSERVATIONS

The spectroscopic observations were made with the coudé spectrograph housed in the 2.1 m telescope building on Kitt Peak, but imaging was done by the 1 m auxiliary feed telescope. Camera 5 and grating C were used to deliver a linear dispersion of ~15 Å mm^{-1} at Hα. The detector was a Fairchild CCD-211. The pixel geometry consists of rectangular diodes of 14 x 18 μm. Together, the spectrograph and the detector yielded a bandpass of 87 Å, centered on Hα at λ6563, with a spectral resolution of approximately 1 Å. For most of the observations, photon noise limited signal-to-noise ratios of ~150 were secured. Errors which affect the photometric results stem from the subjective process of fitting a continuum (performed at a CRT console), from the blending of the Hα wing with the carbon lines, and from numerous telluric water-vapor features distributed around Hα. Efforts were made to assure internal consistency, so that variations could be discussed with confidence. However, the disturbance of the carbon lines by the Hα wing is itself non-constant, since that wing varied significantly throughout the cycle.

LINE PROFILE VARIATIONS

We discuss here only those results which would not be readily obtained with conventional photographic detectors. Figure 1 shows a set of spectral line profiles for a grid of standard B stars from which we have derived the properties of the ionized carbon lines. The set shown here has very nearly the same photospheric temperature, but differs in surface gravity, with the highest gravity at the top. The significance of the surface gravity is its effect on the gas and electron pressure and density in the line formation region of the atmosphere. A reduction in surface gravity results in lower pressures and densities, and consequently in increased fractional ionization of each atomic species. It would seem, therefore, that carbon is behaving in a normal fashion. However, detailed calculations of stellar atmospheres in this range of effective temperatures (~20,000 K) reveal that carbon is more than 98% singly ionized regardless of the pressure. If further ionization to C III were occurring appreciably, the lines of C II should weaken with decreasing gravity, but we observe them to strengthen. Our interpretation is that the dominant effect is not ionization but variation in the continuous opacity of the atmosphere. At these temperatures, hydrogen is fully ionized, and the principal opacity source is free-free (electron-ion) interactions and some bound-free (photoionizations) of remaining hydrogen atoms. A reduction of density reduces the continuous opacity and thus increases the ratio (ℓ_ν/κ_ν) of line-to-continuous opacity, resulting in stronger lines.

Figure 2 shows a sequence of observations of BW Vul, the first three of which are from the single pulsational cycle of July 11, 1979. We note that the carbon lines exhibit variations not unlike those of the differences between giant and main-sequence stars. In BW Vul it is the

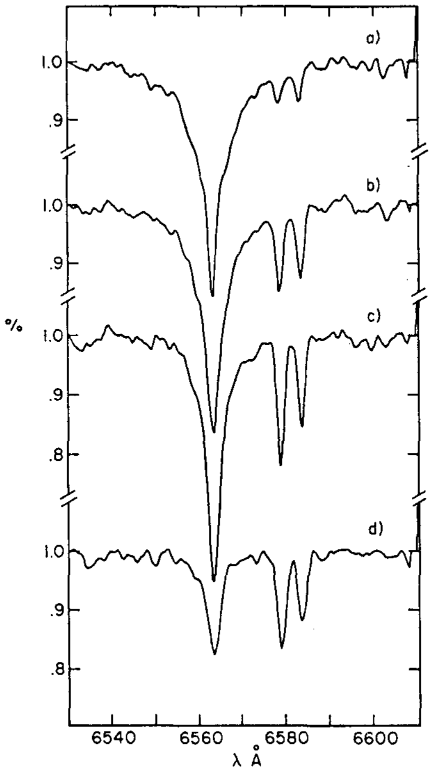

Fig. 1. Normalized intensity profiles of Hα and C II for four standard B stars:
(a) HR 7929, B2 V
(b) HR 8335, B3 III
(c) HR 6714, B5 Ib
(d) HR 8279, B2 Ib

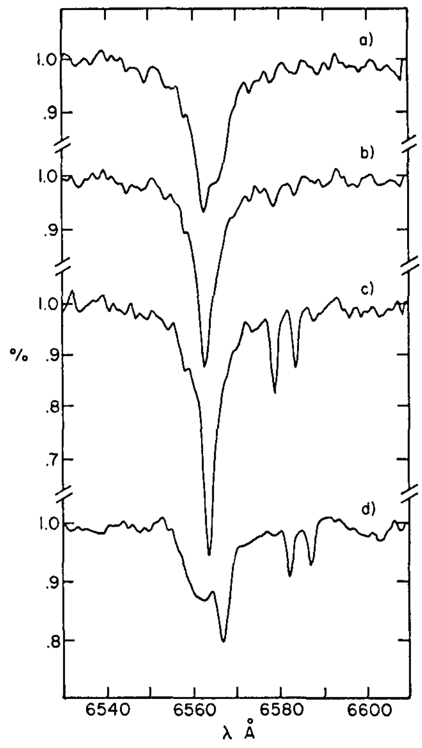

Fig. 2. Normalized intensity profiles of Hα and C II for BW Vul at selected phases:
(a) 8:13 UT
(b) 8:31 UT
(c) 11:10 UT
(d) 10:58 UT, 1979 April 30

pulsation which induces the variation in pressure and density while the surface gravity remains nearly constant. By analogy, we infer that it is the optical depth scale variations caused by changes in the continuous opacity that cause the observed variations in the strength of the C II lines.

Our interpretation implies that as the pulsation cycle proceeds, the formation of spectral lines occur at different optical and geometrical depths, and, therefore, that the radial velocity that is measured from the line cores may not always be representative of the plasma kinematics. Proper treatment of the problem will require hydrodynamical computations with proper attention to radiative transfer.

Figure 3 shows, in more quantitative terms, the nature of the

https://doi.org/10.1017/S0252921100081720 Published online by Cambridge University Press

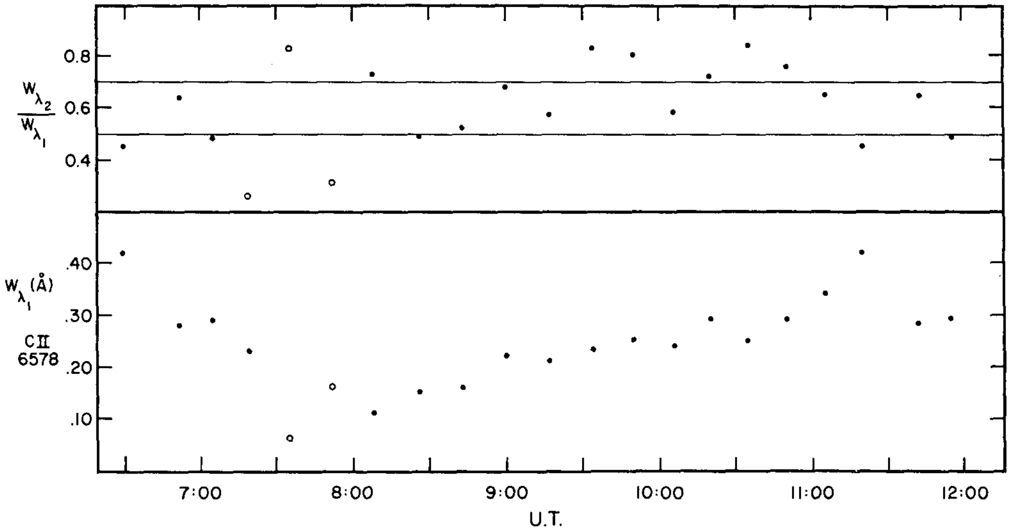

Fig. 3. (Upper) The ratio of the equivalent widths of the carbon lines in the sense W(λ6582)/W(λ6578). (Lower) The equivalent width of the C II line λ6578 as a function of time. Phase overlapping has been done at the end points to facilitate comparisons.

variation of the C II lines. The growth in equivalent width occurs while the radial velocities are negative, which signals expansion of the atmosphere and hence reduction of pressure and density. The rapid growth at the end (10:30-11:30 UT) is accompanied by a rapid decrease in the ratio of equivalent widths.

The significance of the change in that ratio is that the lines appear to be desaturating (their oscillator strengths are in the ratio 1 to 2) while their equivalent width is increasing. One interpretation of that behavior is that the optical depth scale has changed sufficiently so that the mean free path of photons exceeds the geometric dimensions of the region in which a coherent velocity gradient exists in the outward moving plasma. In effect, from the viewpoint of radiative transfer, a macroturbulent velocity field has become microturbulent, and desaturation of the absorption lines occurs.

HELIUM IONIZATION AS A DRIVING MECHANISM

In the outer atmosphere, well above the region of optical continuum formation, our models for B stars with T_{eff} = 20,000 K show that helium is ~50% ionized. The fractional ionization as a function of continuum optical depth (5000 Å) is shown in Figure 4 for two such models, one with log g = 3.5 and one with log g = 4.0. While remaining the order of unity, the ratio of He I/He II displays considerable sensitivity to

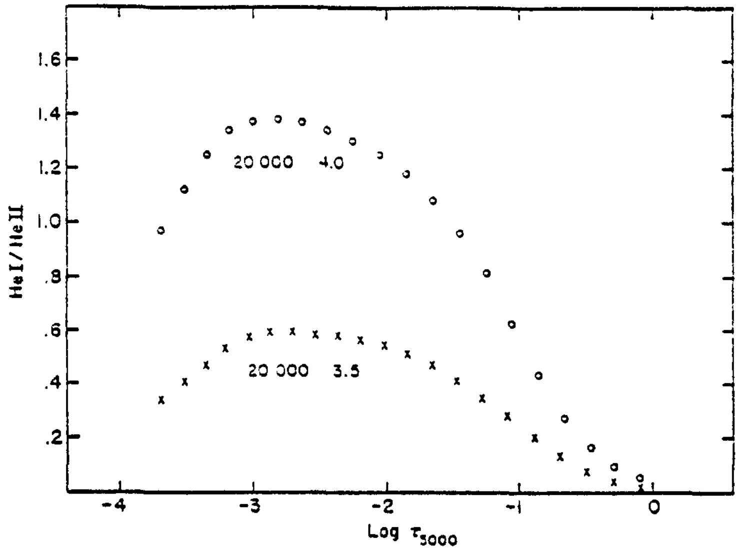

Fig. 4. The ratio of neutral to ionized helium as a function of log optical depth at 5000 Å for two model atmospheres. The main difference between the two models at any optical depth is a pressure difference of approximately a factor 2.

surface gravity, which implies pressure sensitivity. Shifting the effective temperature by as little as 10% upward or downward drives that fraction appreciably from unity, leaving the helium essentially all ionized or all neutral, respectively. Thus this unique circumstance prevails over a relatively narrow strip of the H-R diagram which corresponds closely to the region of the classical β Cep stars.

The compressions and rarefactions which accompany a pulsation cycle in BW Vul induce pressure variations similar to those represented by the two models shown in Figure 4. With the ionization fraction near unity, such pressure oscillations are capable of shifting the ionization fraction appreciably, thereby causing exchanges of energy from thermal to ionization and vice versa. If these exchanges occur quasi-adiabatically, the requisite conditions for a thermo-dynamical heat engine can be realized, so that positive work is done over the cycle to compensate for dissipative losses and thereby to drive atmospheric pulsations.

In our scenario the compressional phase is characterized by a transformation of the log g = 3.5 model to the log g = 4.0 model, resulting in a twofold increase in pressure largely independent of optical depth. The increased pressure induces recombination of ionized helium, a process characterized primarily by the emission of resonance photons (∿500 Å for helium). In Figure 5, derived by the aforementioned transformation of the two models shown in Figure 4, it is seen that most of the recombination energy is liberated in a narrow zone of continuum

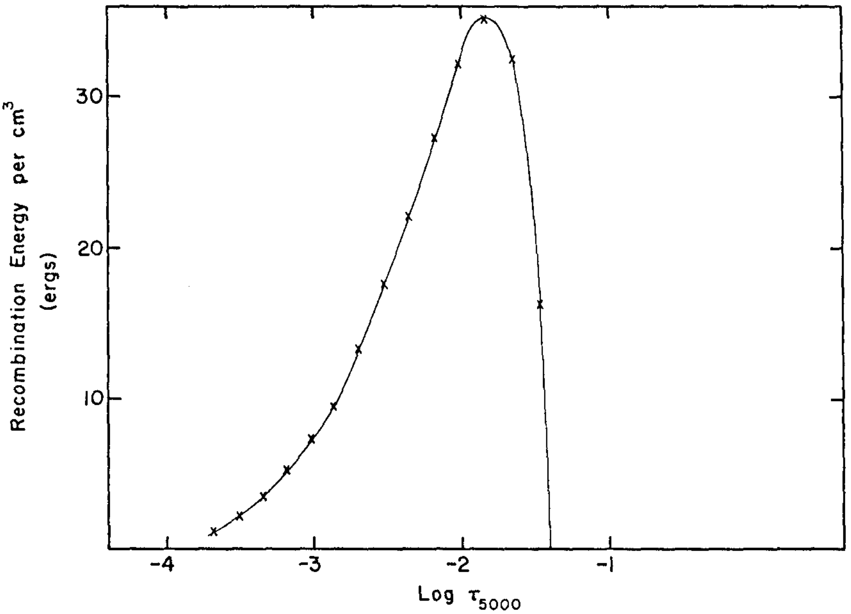

Fig. 5. Released recombination energy of helium as a function of log optical depth at 5000 Å when changing a model atmosphere at T_{eff} = 20,000 K from log g = 3.5 to log g = 4.0, i.e., changing the pressure by approximately a factor of 2.

optical depth, centered on log $\tau_{5000} \approx -1.8$. While this region is optically thin for 5000 Å photons, it is optically thick for 500 Å photons due to He I bound-free opacity. Thus the recombination energy is largely thermalized, thereby adding heat to the gas when it is hottest (i.e., most compressed). The density in this recombination region is increasing as inward-moving gas approaches the relatively stationary gas at log $\tau_{5000} \geqslant -1.8$. An external observer may then detect a doubling of absorption lines and a reduction of B - V color due to compression and recombination heating. The overheated gas now expands and reverses the cycle, and the increasing ionization resulting from the reduction of pressure and density extracts thermal energy while the gas is coolest. Adding thermal energy at the highest temperature phases and removing it at the lowest ones is the requirement for positive work from a heat engine.

It is our proposal that the observed oscillations are, in terms of amplitude, primarily confined to the atmosphere of BW Vul and of β Cep stars in general. If our mechanism is the only destabilizing process, then the interior regions can be thought of as coupled by high impedance and thereby affecting, but not controlling, the oscillation. Conversely, if an interior destabilizing mechanism is at work, our mechanism may act as an amplifier for interior, low amplitude oscillations coupled through high impedance.

We are proposing that the oscillation of BW Vul (and perhaps of all β Cep stars) is confined to the atmosphere alone, and is destabilized and driven by the helium ionization heat engine. The interior of the star, acting as a high-impedance coupling, may participate very little in the oscillations but controls the period.

ACKNOWLEDGMENTS

We thank Dr. Geoffrey Burbidge, Director, Kitt Peak National Observatory, for generous support, and Mr. Paul Scott for considerable assistance with the necessary software.

NOTES

1. Operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

DISCUSSION

PERCY: Two things intrigue me about this particular mechanism: First, it is derived from a very close analysis of what is actually observed. Other mechanisms depend on a series of unproven links from one phenomenon to another. Second, it is extremely promising that it seems to peak at the middle of the β Cephei strip and provides an explanation as to why the strip occurs where it does.

YOUNG: It is very temperature sensitive.

SIMON: It remains to establish whether this driving outweighs the damping that certainly goes on below.

YOUNG: If we add up the energy available in the surface layers we find larger contributions as you get down to deeper more massive layers. Eventually, the driving quickly stops because the temperature ionization becomes more important than the pressure ionization. The heat engine will only operate at relatively shallow optical depths in the continuum. We don't think we need to worry about the deep damping. It is a local surface mechanism.

J. P. COX: My question about this very interesting mechanism is, is it sufficient? Can it excite stars by itself?

YOUNG: For the typical dimensions of BW Vul you have an ability to exchange 4×10^{33} ergs total. If that is anything like what is dissipated in a cycle, then you've got enough energy to do it.

M. SMITH: The instability zone in the H-R diagram coincides pretty closely with the Stellingwerf opacity bump mechanism zone. It may be important that both mechanisms that depend on helium ionizations come into play for the same star. On another point, Percy mentioned that the Dennis Ebbets paper on ρ Leo shows extremely erratic line profile and strength variations. We have independently come to the conclusion that there must be changes in the continuous and not the line opacity. I take it that supports what you are saying.

https://doi.org/10.1017/S0252921100081720 Published online by Cambridge University Press