THE LINE PROFILE VARIABLE B STARS

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I. INTRODUCTION

I would like to summarize the observational status of a new and interesting group of stars which I have dubbed, not too imaginatively, the line profile variable B stars. These stars were apparently first recognized as a class by Petrie and Pearce (1962) in a survey of 570 B stars. In that study they called attention to "line width variations" in high dispersion photographic spectra of 14 early B stars. Since then there have been several reports of variability in studies of the spectra of 10 Lac, ι Her, and 53 Pic (Grygar 1964, Chochol and Grygar 1974, 1976, Underhill 1966). However, given the low S/N and the low quantum efficiency of the photographic emulsion it has been difficult until recently to make quantitative statements about the profile activity.

The profile variables are of interest to the investigation of β Cephei variables because these B stars surround the β Cephei variables in the H-R diagram; many of the latter are themselves profile variables. I shall keep these two types of stars separate in this paper. It is an intriguing possibility that the β Cephei stars may actually represent only the most easily observed "tip of the iceberg" of a much larger class of variable stars.

II. RECENT HISTORY

My "rediscovery" of these variables dates from observations made in November of 1975 (Smith and Karp 1976) with the self scanned Digicon detector at the coudé focus of the 107-inch telescope at McDonald Observatory. The initial observations were made in two or three 100 Å-wide spectral regions. Each showed that lines of a number of different ions and elements showed the same changes in shape. Not surprisingly the variations are most visible in lines of heavy elements for which the thermal broadening is small.

The basic trait of these spectral variations is that the line profiles change their width and asymmetry with little accompanying change in radial velocity (line centroid).

In the last 1-1/2 years I have observed these variations with a resolution of 0.1 Å using two other spectroscopic instruments, the coudé scanner and, lately, (exclusively) the coudé Reticon. Both instruments give a resolution of 0.1 A. I have also had varying degrees of success observing the variations with the 82-inch photographic coudé system, with the Copernicus satellite (U1 mode), and photometrically.

Figure 1 shows the known line profile variable stars and the distribution of "classical" β Cephei stars (Lesh and Aizenman 1973) in the narrow-band photometric β vs. Q diagram. The star λ Ori A may soon be added to the list, but this possibility needs to be confirmed carefully next season. All but two of the northern, sharp-lined (V_{rot} sin i < 50 km/sec) O8 to B5 stars, in luminosity classes V to II and brighter than m_V = 5 that I have investigated (Figure 1) show profile variations. The exceptions appear to be τ Sco and 3 Cen A. The latter is a Bp He-3 rich

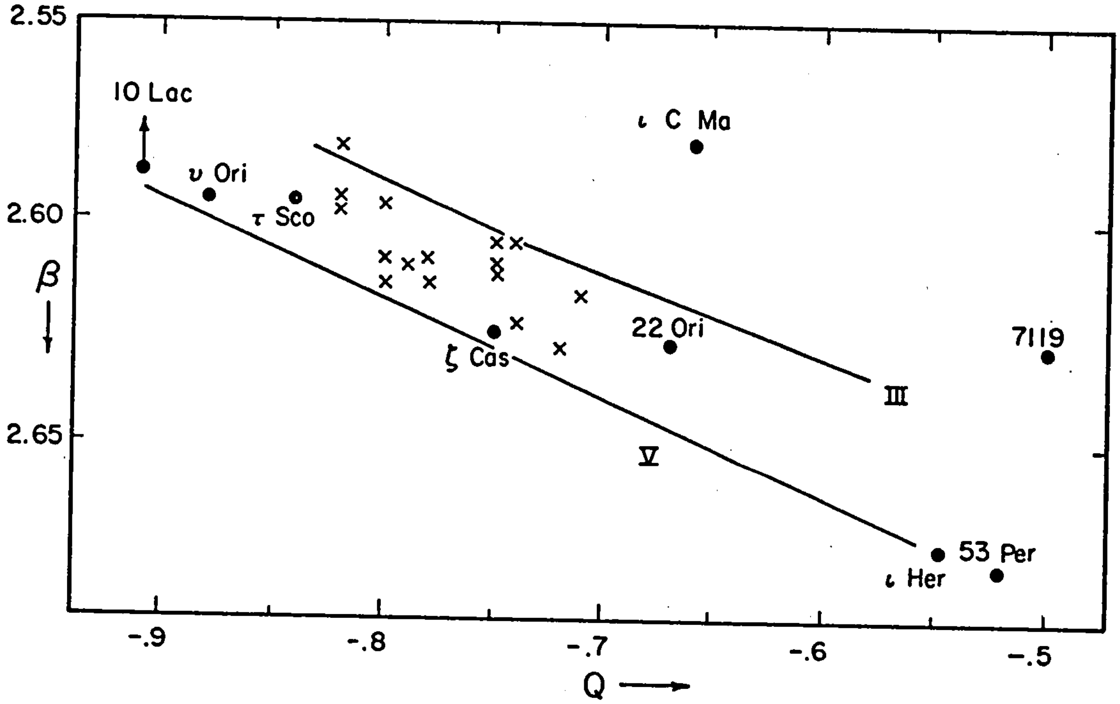

Figure 1: The β vs. Q photometric diagram for the bright, northern profile variables (except τ Sco). Crosses are known β Cephei stars.

star. So far the search has been restricted to the slow rotators because unless the amplitude of the profile changes were very large I could not detect them in rapid rotators.

Recently I searched for variability in the supergiants Rigel (B8 Ia) and Deneb (A2 Ia). So far it appears that any profile changes must be small if they are present. However, ρ Leo (B1 Ib) does appear to show variations.

III. EVOLUTIONARY STATUS

The masses of the profile variables appear to extend at least from 7 $M_\odot$ to 22 $M_\odot$ (Smith 1978) along the main sequence. Three of these stars, 10 Lac (Lac Ob Ib), 22 Ori (Ori Ia), and υ Ori (Ori Ic), are known members of clusters or young associations. Except for υ Ori, which is very young (Warren and Hesser 1978), even these stars are probably well evolved along the main sequence phase. On the other hand, at least four of the sample depicted in Figure 1 have photometric β indices typical of main sequence stars. Putting all these signs together certainly a reasonable statement is that profile variability occurs during both H core-burning and post H-exhaustion evolutionary phases.

IV. LINE PROFILE VARIATIONS

To observe the profile variations it is the usual procedure to monitor intermediate strength lines of a multiplet of a heavy ion for 1/2 to 1 hour. For B3 to B5 stars I observe the Si II $\lambda\lambda$4128, 4130 equal-strength doublet; for B0 to B2 stars, the Si III $\lambda\lambda$4552, 4567, 4574 triplet; for late O stars, the Si IV λ4654 line.

The accumulating data show that the profile variations are periodic and can be easily reproduced with models having traveling waves (nonradial pulsation). The observed periods are sufficiently long (5-15 hours) that they must be identified with g-modes, according to nonradial pulsation theory (e.g. Osaki 1975). Most if not all of the variables appear to change their pulsation amplitudes and periods on a timescale of a month or two. Such changes have probably been observed in progress three times thus far. Many periods have been observed to recur in individual stars, however, showing that period changes are not isolated events.

In order to produce profile variations without accompanying radial velocity changes one needs to vary a "macroturbulent" velocity field across the stellar disk in an ordered way. Struve (1955) first suggested rising and falling "prominences" on the surfaces of β Cephei stars.

Later Christy (1967) and Osaki (1971) showed that the spherical harmonic velocity distributions expected from the traveling wave modes of nonradial pulsation can produce large changes in line profiles. Smith (1977) showed that these velocity fields can actually be matched to observed profile changes in three β Cephei stars and to the largest changes in the profile variable B stars.

Figure 2 shows a progression of a modeled traveling wave cycle in terms of the distortion of the line profile.

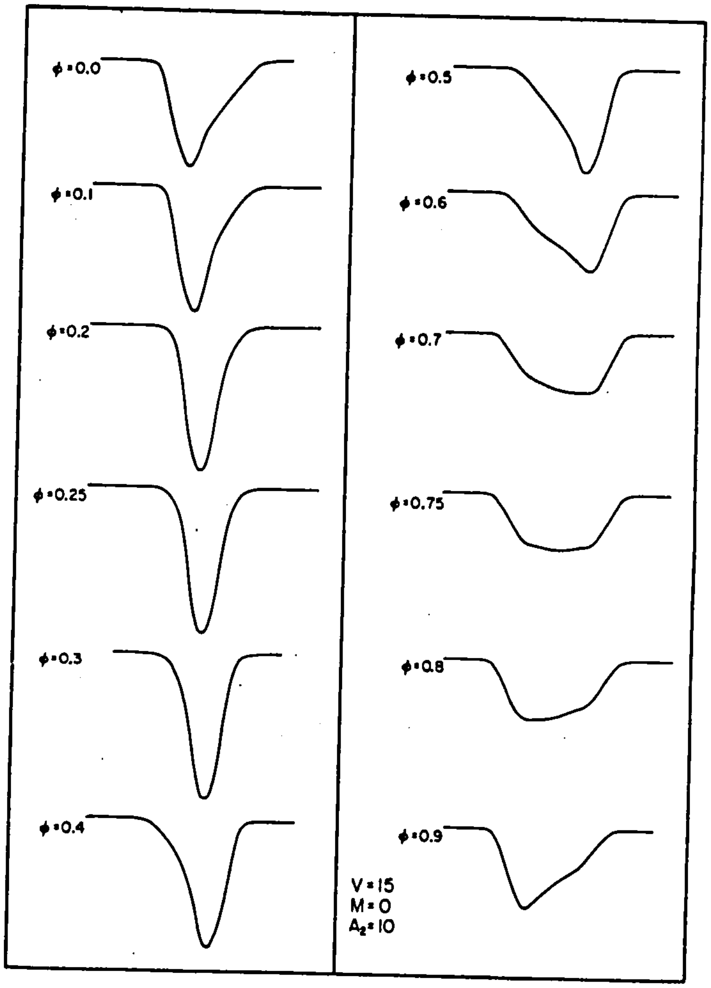

Figure 2: Progression of a model line profile with time through a traveling wave ($\ell = 2$, $m = -2$) cycle.

A few clarifications about this diagram can be made:

1.) The profile distortions depend upon the interaction of the rotational and nonradial pulsational velocities. The distortions are always maximal when the two velocities are comparable.

2.) The retrograde modes ($m > 0$; traveling waves running azimuthally opposite to the sense of stellar rotation) can be clearly distinguished from the direct modes. For retrograde modes the progression of phases depicted above runs backwards with time (cf. Figure 6, 22 Ori).

3.) The morphological changes shown are computed for a specific nonradial mode ($\ell = 2$, $m = -2$). However, the changes often can be closely approximated by several other traveling wave modes of the same phase if one changes the velocity amplitude.

4.) If the profile variation is reasonably large a single observation fixes the phase. Therefore, unlike the case of radial velocity or light variability, a few profiles suffice to determine a period.

Statement 4 must be qualified by stating the important assumption that only one mode is visible at a time. In general I have invoked an "economy of assumptions" principle and fit the profiles to a single period if that is possible (it usually is). In the earliest data I often only had 5 to 7 observations per observing run in order to determine a pulsation period. The more typical recent figure is 12 to 18 observations, but this cannot always be maintained. As an experiment I have "withheld" a few profiles from the main data set. After determining a period and amplitude from this larger data set, one can predict model profiles for the withheld cases. The predicted profiles successfully match the "withheld" observed profiles (Smith 1978). This demonstrates the self-consistency of the periodic hypothesis. I have also deliberately switched two profiles in their time sequence and have then been unable to solve for a (false) period.

One can summarize the results from most of the profile modeling by stating that a direct, sectorial ($m = -\ell$) mode seems to be required to fit the variations. Modes having $|m| < \ell$ produce radial velocity variations but negligible profile variations and are therefore unacceptable. The observed pulsational velocity amplitudes vary from a large (8 to 10 km/sec, 53 Per) to a small (3 to 4 km/sec) value, sometimes in a single star over a few months. For a typical S/N, spectral resolution, and number of profiles used in the observations (e.g. 200, 0.10 Å, 12) the threshold pulsational amplitude is probably 2 to 3 km/sec. The phase resolution per observation, $\delta\phi$, is 0.03 to 0.05, depending on the data quality and velocity amplitude. Finally, I will add that in the best cases I might be able to discover a secondary mode but only if its amplitude were at least 1/3 that of the primary mode.

The observations are invariably fit best with traveling wave models in which local particles move primarily <u>radially</u>. This is surprising because nonradial theory predicts that material should move primarily horizontally in oscillations of such long periods (Osaki 1971).

Examples --

Table 1 gives a summary of periods observed for six stars along with the numbers of observations used to derive them for several observing runs of 3 to 7 nights. The main point is that several periods are present at various times

TABLE 1

Summary of Useable Observations
on Several Line Profile Variables (May, 1978)

Star	Periods Observed (hrs.)	No. Runs/No. Profiles	Amplitude (km/sec)
53 Per	3.59*	1/5	8
	4.50:	1/3	12
	7.29(*)	2/4,5	9-12
	11.43	1/7	12
	14.6	2/8,8	7-10
		Total 6/35	
ι Her	4.92**	1/15	5
	9.92**	4/2,6,15,18	4-6
	13.92**	3/5,13,18	4
	15.4	1/17	4:
		Total 7/76	
10 Lac	4.88	4/4,5,15,5	4-10
	?	1/2	28
		Total 5/31	
22 Ori**	8.95**	3/8,4,11	5
	4.55**	2/5,11	
		Total 5/24	
η Ori	11.0	1/4 (1 cycle)	4
ζ Cas	21.5:	2/11,2	5
		Total 2/13	

GRAND TOTAL: 184 OBSERVATIONS

* Period once observed simultaneously with another.

** Mode observed changing to another mode.

but the most recently observed stars (ι Her, 10 Lac, 22 Ori) show frequently reoccurring periods. By far the most recurrent period ratio is 2.0. Figures 3 through 8 show examples of profiles of the six profile variables modeled with a traveling wave solution (usually $-m = \ell = 2$).

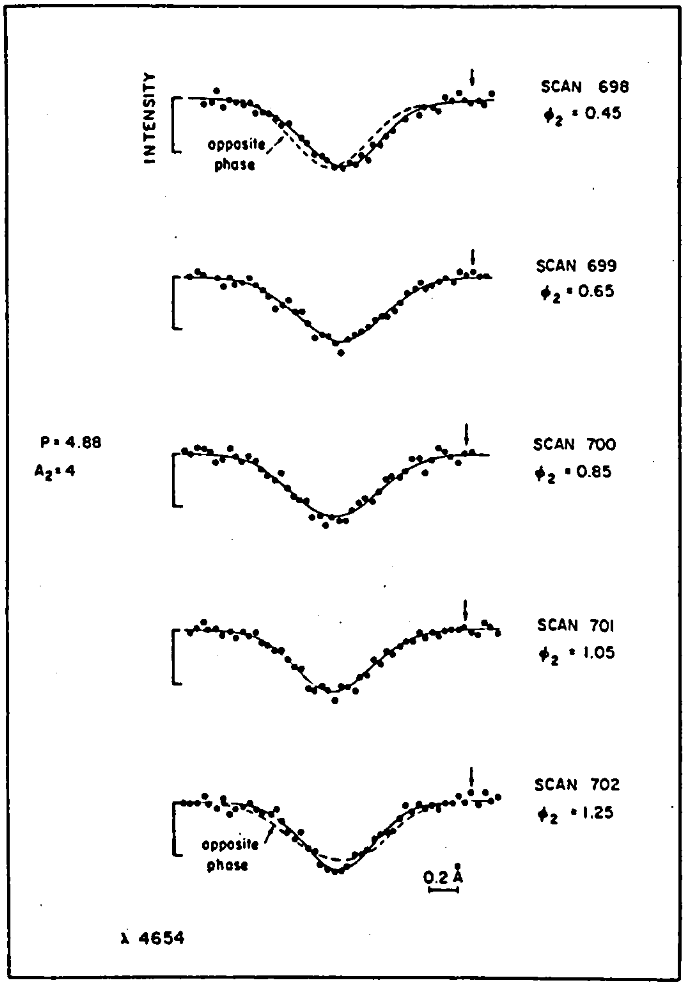

Figure 3: Contiguous observations of the λ4654 line of 10 Lac through a full pulsation cycle on Dec. 31, 1977. Solid and dotted lines indicate models of the nonradial pulsation profiles at the correct and opposite (for comparison) phases, resp. The indicated period and (small) amplitude are in hours and km/sec.

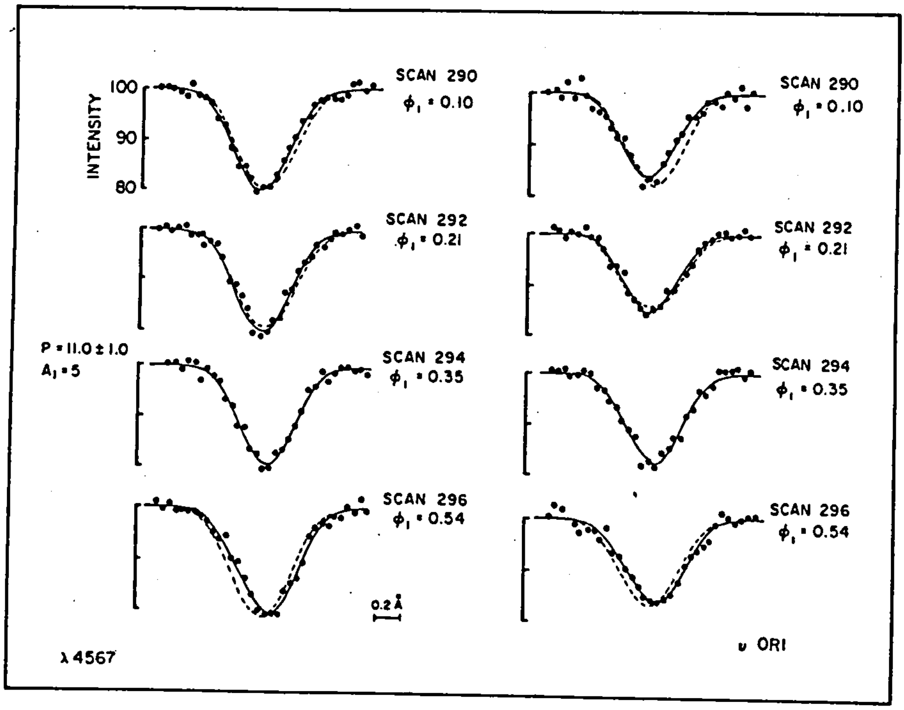

Figure 4: Observations of the 4552 and 4567 lines of the very young B0 star υ Ori during one night in December, 1976. On this and following diagrams the dashed line on selected profiles indicates the unperturbed profile that would occur if there were no pulsation.

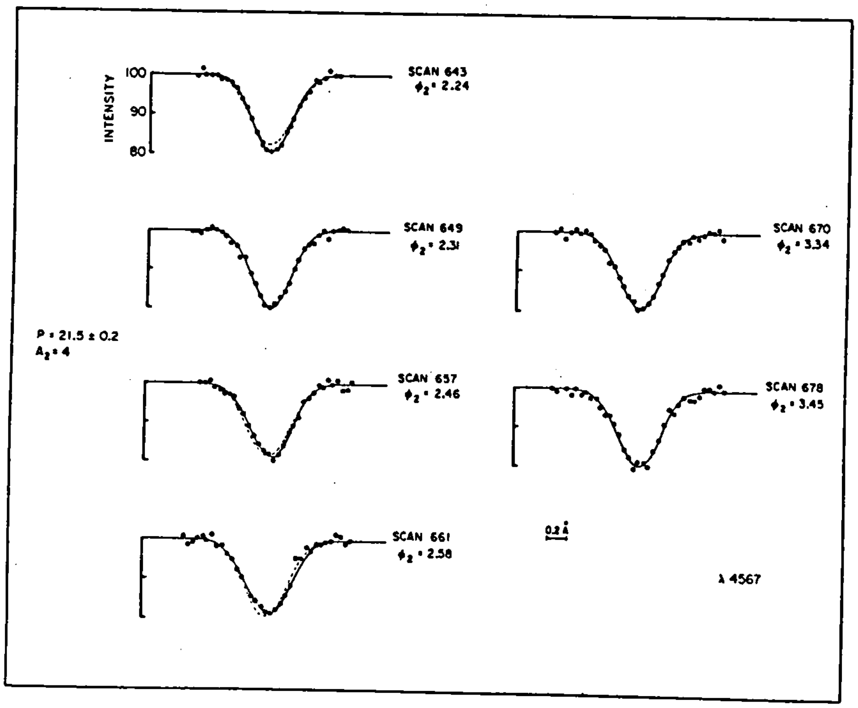

Figure 5: Observations and nonradial model fits to λ4567 of ζ Cas in August, 1977. Note the long period.

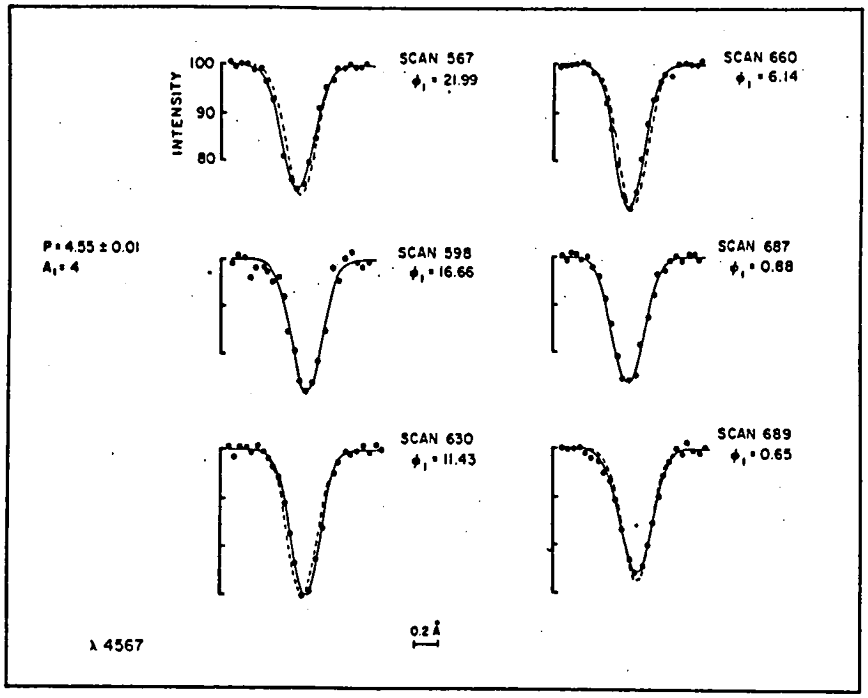

Figure 6: Observations and nonradial fits to λ4567 of 22 Ori in August, 1977. The reversed sequence of cycles indicates the presence of a retrograde mode.

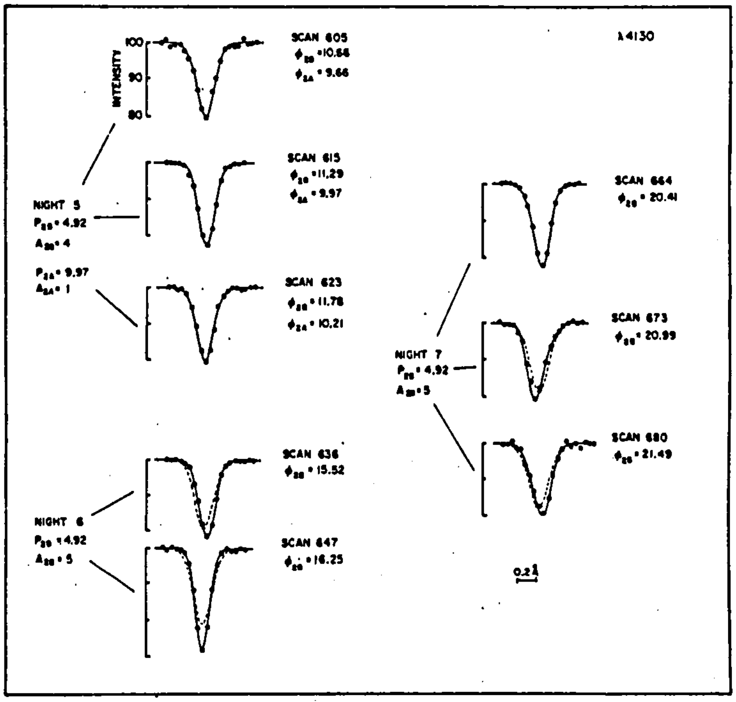

Figure 7: Observations and nonradial fits to 4130 of ι Her during latter three nights of a run in August, 1977 (see Smith 1978).

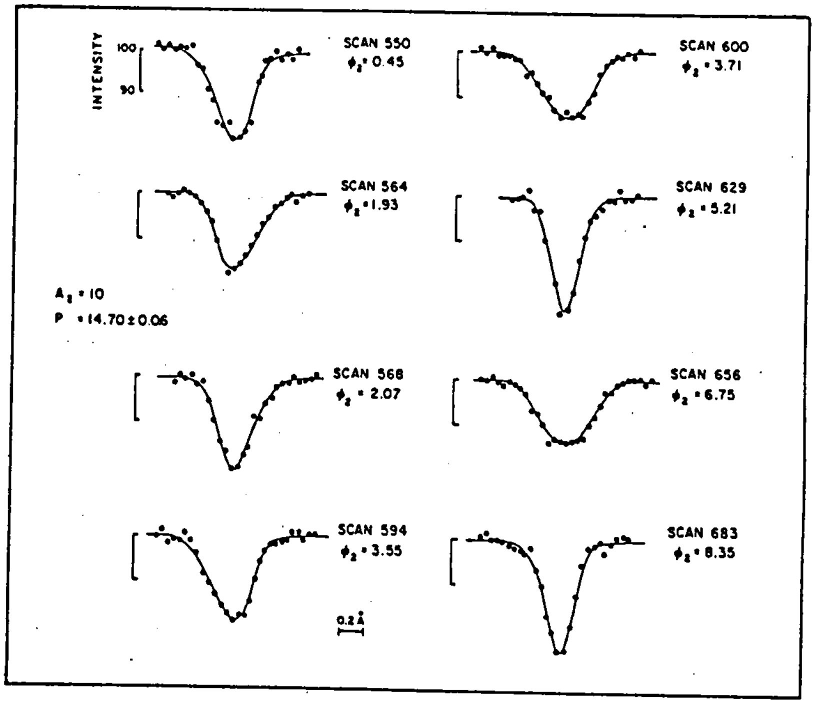

Figure 8: Observations and nonradial fits to λ4128 of the large amplitude variable 53 Per during August, 1977 (Smith and McCall 1978).

Estimates of the errors associated with the indicated periods and amplitudes can be found in Smith and McCall (1978) and Smith (1978). Two additional points of interest to note in these figures are the retrograde mode for 22 Ori (Figure 6) and the rather long period, 21 1/2 hrs., for ζ Cas (Figure 5).

V. LINE STRENGTH VARIATIONS

Because these stars are sharp-lined several of them, especially ι Her and 10 Lac, have been traditionally used as equivalent width standards in differential curve of growth analyses of other B stars. However, I wish to introduce a serious caution in their being put to this use. The metallic lines often vary in strength and this means the stars are not good standards. The amount by which they vary seems to be roughly proportional to the pulsational amplitude. The most extreme change found was a 100% variation in the strength of λ4654 in 10 Lac over two nights. Both 10 Lac and ι Her have occasionally shown 50% variations over a few nights. The variations during a particular cycle are certainly smaller, probably averaging 15 to 20% (assuming line strengths of 50 to 70 mÅ (Smith 1978). Both the published and more recent unpublished data indicate that the strength variations correlate well with pulsation phase. The lines reach maximum and minimum strengths at phases near 0.65 and 0.15, respectively. Determining the detailed shape of the "line strength curve" in the future will be a worthwhile enterprise because it provides quasi-photometric information about the pulsation mode index ℓ that is complementary to what can be learned from the profile shapes. (This is because weak and strong line areas add linearly over the stellar disk, whereas opposite velocities occurring on different regions of the disk produce a smearing effect on the profile and do not cancel.)

Having also investigated the <u>cause</u> of the line strength variations, I have found (Smith 1978) that these changes cannot reasonably be caused by surface variations of temperature or gravity. At the same time, the strong lines do vary in strength proportionately more than the weak lines do. This is a clue that a "microturbulence" is present and that it increases at certain phases. Quantitatively, the required velocity is comparable to the atmospheric sound speed, if one assumes the $\ell = 2$ mode. Therefore, it is quite possible that we are witnessing the generation and propagation of shock waves at $\phi \approx 0.65$. Interestingly enough, this time corresponds to the phase during which atmospheric material in the wave is falling and compressing material below it.

VI. PHOTOMETRIC VARIATIONS

The question arises do the line profile variables also show light variations? Percy (1970) first showed that very small variations exist in a few of the Petrie-Pearce stars. However, he was unable to derive light curves or periods. Percy and Lane (1977) and Africano (1977) recently observed 53 Per for one and two nights, respectively. They each found peak to peak variations of 0.01 mag. Africano's observations were consistent with a 7.3 hr. period derived a few nights later from line profiles.

In an effort to add to our meager knowledge of the photometric behavior of these stars, Ron Buta observed 53 Per for several nights during November and December, 1977. As Figures 9 and 10 show, variations of several hundredths of a magnitude were the rule at these times. To complement this coverage I observed the λ4129 doublet <u>photographically</u> in this star on three nights in November (JD 2442466-8).

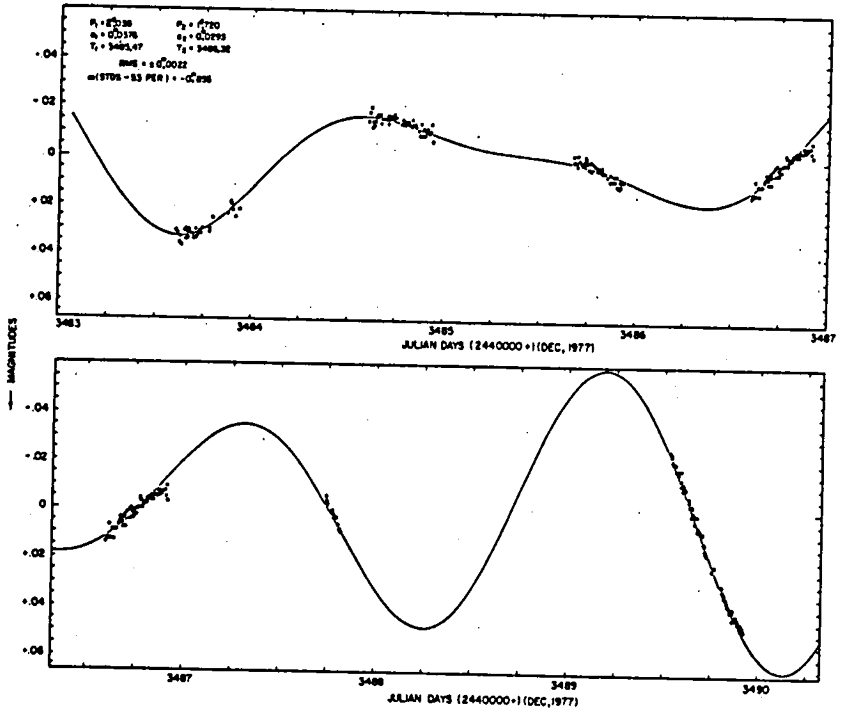

Figure 9: Light curve (Strömgren v-filter) of 53 Per obtained by Mr. Ron Buta in December, 1977. The solid line and indicated parameters apply to a two-sine curve fit to this data.

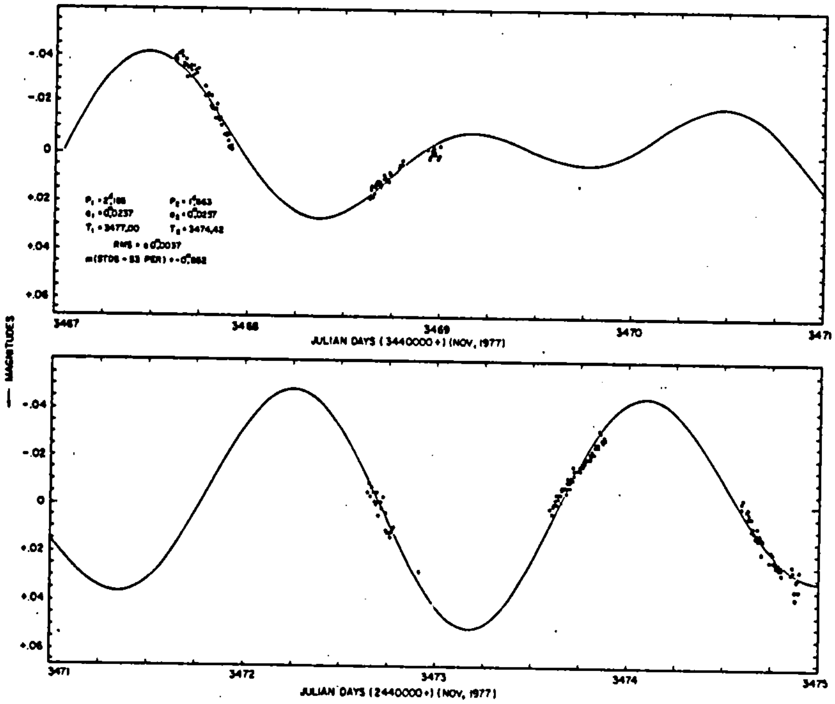

Figure 10: Buta's light curve for 53 Per in November, 1977.

These profiles and modeled fits are shown in Figure 11. Naturally the S/N is low here, but it seems to be sufficient to show that a surprisingly long period of about 1.9 days was dominant at this time.

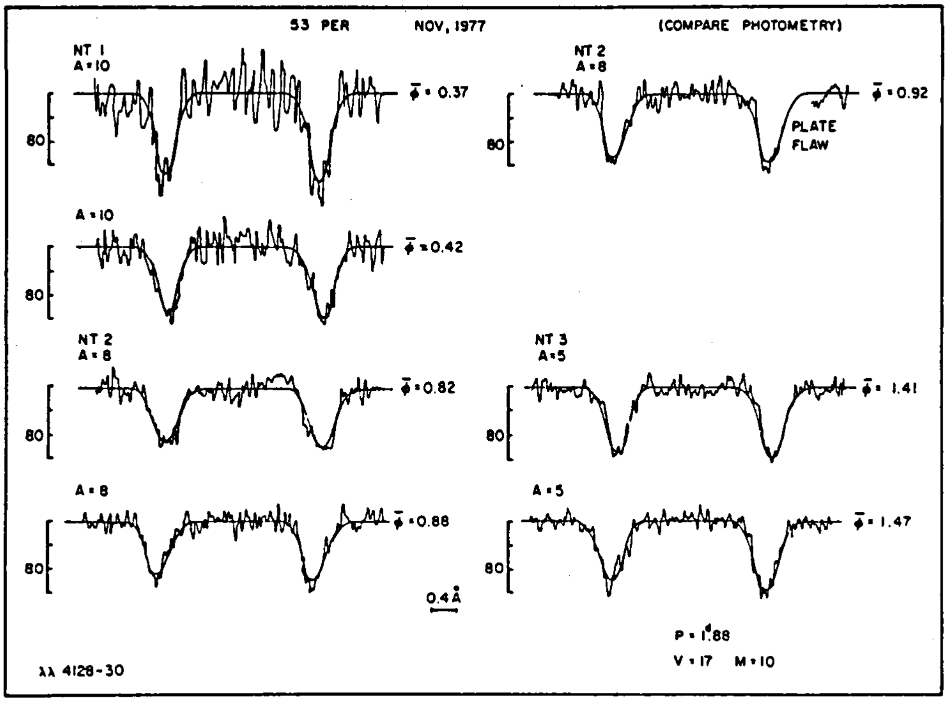

Figure 11: Photographic observations for the λλ4128-30 doublet in 53 Per obtained by the author on three nights in November, 1977. The latter two nights overlap with the first two nights of photometric coverage shown in Figure 10.

The modeling of Buta's photometric data on 53 Per has been investigated. Note first that phase reversals in both data sets occur near JD 2443469.5 and 2443485.3. Their appearance implies the interference of at least two modes. Therefore I have attempted to fit the photometric data sets independently with a minimum of two sine curves. The best solution in both cases is a pair of periods which average 1.87 ± 0.01 days. The two components are nearly of the same amplitude but differ in period by several percent. It should be added that I attempted to model the two data sets with many other pairs of periods, including those corresponding to "alias" peaks in the power spectra of the data. However, they did not allow a good solution.

The quality of the fit to the December data as shown in Figure 9 is remarkably good (r.m.s. is ±0.0022 mag.), but it is wanting in the November observations (Figure 10). Perhaps a third mode is present in November. On the other hand the data span is so short that a truly credible solution is not possible. In fact, if it were not for the spectroscopic agreement in Figure 11 one could not be sure that either solution given in Figures 9 or 10 is even approximately correct. As it is the spectroscopy offers an important confirmation.

Two periods differing by a small amount have been observed in one other star, the white dwarf R548 (Robinson, Nather, and McGraw 1976). The existence of these periods has been convincingly ascribed by these authors to nonradial m-mode splitting. Such may be the case for 53 Per as well. If so, it would appear that a tesseral mode ($m < \ell$) can occur at least sometimes along with the sectorial mode.

Taken at face value, this 1.87 day period of 53 Per is interesting because it is about three times the 14.6 hour period observed at certain other times. (The multiples, 7.3 and 3.6 hour periods, have probably already been observed in 53 Per too.) This is intriguing because it is well known that subharmonics of $\omega/3$ occur commonly in nonlinearly oscillating systems. Perhaps there is an additional clue here that explains the period changes. For example, it may well be that like the large amplitude ZZ Ceti (DA) stars the line profile variable B stars are overdriven pulsators. Then their nonlinear character could serve as a starting point to build a description of the frequent period changes, especially those involving harmonic factors of two.

I wish to thank Fred Campos for his aid in the spectroscopic reductions and profile modeling. I am also indebted to Ron Buta and John Africano for permitting me to exhibit their superb photometric observations prior to their more complete description and publication. This work has been supported by N.S.F. Grant AST 77-06965 and N.A.S.A. Grant NSG-5167.

REFERENCES

Africano, J. 1977, I.A.U. Comm. 27 Info. Bull. Var. Stars, No. 1301.

Chochol, D., and Grygar, J. 1974, *Bull. Astr. Inst. Czech.*, **25**, 231.

____________________. 1976, *Bull. Astr. Inst. Czech.*, **27**, 181.

Christy, R. F. 1967, *A. J.*, **72**, 293.

Grygar, J. 1964, *Bull. Astr. Inst. Neth.*, **17**, 305.

Lesh, J. R., and Aizenman, M. L. 1973, *Astron. Astrophys.*, **22**, 229.

Osaki, Y. 1971, *Pub. A. S. J.*, **23**, 485.

________. 1975, *Pub. A. S. J.*, **27**, 237.

Percy, J. R. 1970, *A. J.*, **75**, 818.

Percy, J. R., and Lane, M. J. 1977, *A. J.*, **82**, 353.

Robinson, E. L., Nather, R. E., and McGraw, J. T. 1976, *Ap. J.*, **210**, 211.

Smith, M. A. 1977, *Ap. J.*, **215**, 574.

__________. 1978, *Ap. J.*, **224**, ---.

Smith, M. A., and McCall, M. L. 1978, *Ap. J.*, **223**, ---.

Smith, M. A., and Karp, A. H. 1976, Los Alamos Conf. on Solar and Stellar Pulsation, Aug. 3-5th, p. 289.

Struve, O. 1955, *Ap. J.*, **122**, 103.

Underhill, A. B. 1966, *The Early Type Stars*, (Dordrecht: D. Reidel Publ. Co.), pp. 258-9.

Warren, W. W., Jr., and Hesser, J. E. 1978, *Ap. J. Suppl.*, **36**, 497.

Discussion

J. Wood: Do you have any information on the wavelength dependence of the amplitude of the photometric variation, or was this all monochromatic? And what color was the light curve?

M. Smith: These were Stromgren v filter observations. We tried one or two quick tests on that which seemed to suggest it's almost flat, but it's too early to say yet. And according to nonradial theory, for this particular period, temperature-compression effects should dominate the two geometric effects. But we're going to go back and look into this a little more carefully this fall, to confirm or refute that tentative observational result.

J. Wood: So you wouldn't expect any depth dependence of maximum light?

M. Smith: No.

J. Cox: Can you determine a rational velocity from your period splitting?

M. Smith: If I do, the other Texas people, who do this work much more carefully, will laugh at me. It turns out the rotation velocity that I derive for 53 Per spectroscopically is 17 km/sec. And if you take the 13 days between the two phase reversals, you can infer a very accurate period difference. If you are foolhardy enough to play that game, you come up with surprisingly good agreement, and the implied inclination of the star is 60°. But you asked me -- I would never volunteer that otherwise.

Aizenman: Did you find any mode that you interpreted with $m = +2$?

M. Smith: In one star, 22 Ori, there is always either a 9 or a 4.5 hour period. And in every case, the oscillation appears to be going backwards. Therefore, $m>0$, and probably $m \approx +\ell$, but that's all I can say. There also seems to be one β Cephei star which Struve discovered, that is doing this.

Aizenman: Then all the others would have negative values of m?

M. Smith: Exactly.

Shipman: Have you looked in this or any other star for a variation in the line ratios, like Si III/Si IV, to try to detect temprature changes over the cycle? I think you could do a pretty sensitive job on this.

M. Smith: I think so too, with this data. Some of the signal-to-noise ratios in this data, by the way, were as high as 700. So you certainly could do that. What I have found, are line strength changes that are correlated with the strengths of the lines, in the sense that a microturbulence would. Unfortunately, in the early B stars, lines of different ionizations are in different wavelength regions. And even though I'm getting 100Å coverage in an observation, that's not enough -- we'll have to wait for Bob Tull's "Octocon," with 800Å coverage.