

THE NONRADIAL OSCILLATIONS OF EPSILON PERSEI. I. A LAWN-SPRINKLING SHOCK

MYRON A. SMITH

National Solar Observatory, National Optical Astronomy Observatories¹

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ABSTRACT

In the course of monitoring Si III line profile variations in ϵ Per (B0.7 III), we have encountered an unexpected phenomenon: the occurrence of time-dependent extended wings in the lines. These wings appear to be primarily controlled by large vertical velocities associated with the primary $l = 4$ nonradial mode in this star and are modulated by a secondary $l = 6$ mode. We have considered a number of physical models for these extended wings and are able to rule out nearly all of them. For example, we find that only a small minority of extended-wing events can be understood through horizontal velocities associated with the spheroidal modes present in the star's atmosphere.

An attractive model that presents itself is borrowed from the (radially pulsating) β Cep stars, namely, the vertical propagation of shocks through the star's atmosphere with the onset of each pulsation cycle. In the case of ϵ Per, the shocks would occur locally just after the phase of maximum upward acceleration. The shock front would proceed around the star with an azimuthally traveling wave, and it would be confined to the equatorial regions. Because of its continuous traveling nature, and concomitant modest mass loss, we refer to the shock as a "lawn sprinkler." With respect to all the principal properties of the extended wings (namely, their frequency, timing, velocity extent, and perturbation on the line strength), the observations can be successfully matched with a lawn-sprinkler model scaled from β Cep star observations. These shocks probably perturb only slightly any mass loss and stellar winds initiated by radiative line pressure in this star. However, they may well encourage the growth of instabilities as the winds are accelerated.

Subject headings: line profiles — shock waves — stars: individual — stars: pulsation

I. INTRODUCTION

It has become axiomatic in high-resolution spectroscopy that the more closely a star's spectrum is examined, the more "abnormalities" are uncovered. This statement has certainly proved valid recently in an intensive spectroscopic IUE-photometric campaign in early November 1984 of the large-amplitude, nonradial pulsator ϵ Per (B0.7 III; Walborn 1971). The information gathered by this campaign has been so rich, and it has touched on so many quantitative measures of nonradial pulsations (NRP) in B stars, that it has become necessary to reorganize the results into a short series of papers. In this first paper, we will describe a new observational phenomenon, the detection of time-variable, extended wings of photospheric Si III lines. At first sight, such an effect may seem arcane. Yet we will argue that it actually falls squarely within the purview of what is probably a universal process in large-amplitude pulsators across the H-R Diagram, be they radial or nonradial, namely, the production and propagation of shocks through a stellar atmosphere. Thus, although the phenomenon reported is novel, the suggested explanation for it is not. One interesting ramification of our conclusion is the confirmation that the particles participating in the wave motion in this star move essentially vertically. Another consequence is the realization that we failed to appreciate the importance of these extended wings in an earlier study based on less extensive data (Smith 1985a, hereafter Paper I). We attributed it then, probably erroneously, to an $l = 1$ or 2 long-period mode.

II. OBSERVATIONS

The observations discussed herein are of even higher quality than those in Paper I. We observed the Si III $\lambda\lambda 4552-74$ triplet in ϵ Per for 11 hr continuous stretches on each of the nights of 1984 October 31 through November 4, using Camera 6 and Grating B-configuration in the coude feed telescope of Kitt Peak National Observatory. The detector used was the No. 3, three-phase, 800×800 TI CCD chip cooled to -100°C . The pixels in this detector are $15 \times 15 \mu\text{m}$ in size. The spectrograph configuration resulted in a wavelength sampling of $43.7 \text{ m}\text{\AA} \text{ pixel}^{-1}$ and a spectral resolution of $110 \text{ m}\text{\AA}$. This resolution was sufficient to oversample the Doppler-imaged activity of interest, i.e., the $l = 4$ and 6 modes present at this time. The typical signal-to-noise (S/N) ratio in the observations was ~ 300 . Typical exposure times were 7 minutes, which is sufficiently short to resolve any of the profile changes we observed. We attempted to maintain a constant time sampling of ~ 10 minutes. In all, over 300 observations were made. In each case that we cite for $\lambda 4552$ line, we have confirmed that the behavior is present in the $\lambda 4567$ line as well, and also in flanking observations in the time series.

III. DESCRIPTION

a) Extended Line Wings

In the course of scrutinizing Si III line profile variations and assigning them to a pair of prograde, sectorial $l = 4$ and 6 modes, we encountered an interesting anomaly not noticed in most other data we have examined of rapidly rotating NRP stars. This anomaly manifests itself as a frequent strengthening of the profile out to and beyond the line's "footpoints," that

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(mythical) point at which the line profile meets the continuum (at about the 99.6% level). This delay in meeting the continuum, or “extension” of the far wings, is strongly time dependent, and it tends to favor the blue wing over the red wing. The lengths or depths of these extensions in the two wings are not correlated, either at the same time or with an appropriate phase lag. Actually, the “anomaly” is the rule: during the five nights of observations we are able to detect some extension in either wing 94% of the time. The phenomenon is also present in observations of ϵ Per presented in Paper I (see especially Fig. 5 of that paper).

Before proceeding with a detailed description of this phenomenon, it should be stated that it is not possible to generate absorption contributions beyond the line's footpoints according to conventional NRP models. This statement applies to low as well as to high degree modes, and to combinations of modes for rapidly rotating stars.² Thus the usual descriptions applied to line profiles, e.g., “broad” and “narrow,” usually refer to their widths at a reference point such as half-maximum and not to their extreme wings, which are normally not influenced much by NRP.

Three figures below have been prepared to represent the behavior of the extended wings. Each profile represents a separate “incident” of perhaps 30–60 minutes.

These incidents are confirmed in two ways: first, by comparing the companion $\lambda 4567$ line in that spectrum, and second, by searching for extended-wing signatures in the two spectra just preceding and following the cited observations. These precautions guard against random and systematic photometric errors caused by a variety of conceivable instrumental sources. Further discussion on this important point is raised in the next paper of this series.

To conserve space in the figures, we show only the upper portions of the profiles, along with the FFT-smoothed fits for reference and noise estimation. The “natural” approach to the continuum is obtained from an all-rotation, macroturbulence (134 km s^{-1}), no-pulsation model and is shown as a thick, dashed line. This dashed line is correct in the sense that it fits a number of observations very well when no extended wing is present and when the two $l = 4$ and 6 oscillations effectively cancel each other over the relevant portions of the line profile. The extended-wing observations in the figures are bracketed by two reference observations (out of a total of five) that do not show extended wings and which fit the dashed-line model profile. The observations are registered in wavelength by two vertical lines. In Figure 1 we define the terms “footpoint,” the “approach to the continuum,” and “line shoulder.” (The terms “far” or “extended” wing in the text will mean any absorption beyond the footpoint.)

Typically, both blue and red wing extensions are well correlated with the phase of the $l = 4$ mode, $\phi(4) = 0.25$. This is the strongest correlation of all we are able to make. To repeat, the blue wing is extended more frequently and more strongly, and it usually goes through its maximum between a $\phi(4)$ of 0.25 and 0.5 (see examples 1 and 2 of Fig. 1). The wing is then usually extended by $\sim 40 \text{ km s}^{-1}$. A red wing usually appears during the interval $\phi(4) = 0.0$ –0.25 (examples 3, 4, and 5 of Fig. 1). At $\phi(4) = 0.25$ the features are occasionally present in both wings (examples 6–10 of Fig. 2; in example 10, the effect is weak but

present in contiguous spectra and in the companion $\lambda 4567$ line). Usually the blue extension builds to a maximum quickly at or just after 0.25 and then declines slowly. During rapid changes variations can be noticed even over 7–10 minutes.

At $\phi(4) \approx 0.65$ the blue feature disappears. At this time the wings invariably do *not* invert or show truncated wings. In fact only on one, or possibly two, out of 13 occasions when we observed $\phi(4)$ did even a small truncation occur. That observation is exhibited as example 15 in Figure 3. In addition, although extended wings are usually not present at $\phi(4) = 0.75$, there are rare and dramatic exceptions when it does occur, as in example 11 of Figure 3 (another example on October 31 is not shown). However, we have noticed that at the times of these observations the phases of the two modes were 180° apart at stellar-disk center. The wave motions were then aligned at $\sim 70^\circ$ in longitude from disk center. In model atmospheres terminology, this corresponds to $\mu = 0.3$ –0.4, an interesting point on the star's equatorial belt, as we will see.

Occasionally at $\phi(4) = 0.0$ and 0.5 “ramps” form in the outer wings. These are shallow absorption features that meet the continuum essentially without curvature and which depart noticeably from an extrapolation of the inner profile. At either of these two phases a ramp can occur on either wing. Examples 12 and 13 show ramps in the “less common wing,” that is, on the wing on the same side of the line as the deepest absorption bump from the $l = 4$ mode. These ramps are reminiscent of strong features that often occur in spectra of several large amplitude β Cep stars. Finally, we show as example 14 another very rare occurrence, a strong extended blue wing flowing naturally into a blue absorption bump in the shoulder of the profile.

There are three important aspects of the extended wings that must be brought out prior to any analysis. The first is that the lines are observed to strengthen slightly when the extended wings appear. In planimetry line profiles observed just before, during, and after the appearance of a strong extended wing, we find strengthenings of 2% and occasionally even 3%. (The measurement accuracy of these measures, judged from results from successive observations, is $\pm \frac{1}{2}\%$.) We can think of two probable causes for an increase in line strength. The first is that depth-dependent velocity field exists. We accept this as the correct general explanation. The second is that pulsationally induced temperature variations across the stellar disk produce changes in the occupation levels of the Si III atoms. It is easy to show that T_{eff} variations expected for the $l = 4$ oscillations, of order $\pm 500 \text{ K}$, are much too small to cause even these modest variations in line strength. Consequently we rule out this explanation.

The second important aspect of the extended-wing observations is that they seem to be correlated with a constructive mode interference at a colongitude of $\sim 70^\circ$ (where we define this term as the angle along the equator from the substellar longitude to the point in question). This corresponds to a destructive interference at the substellar longitude. Good illustrations of this situation are the strong-extension examples 1, 2, and 3. However, this generalization is apparently not valid when the $l = 4$ wave is abnormally weak, as in reference example II (Fig. 1). Exactly contrary $\phi(4)$ and $\phi(6)$ phases tend to beget profiles without any wing extensions at all (see reference examples I [Fig. 1] and V [Fig. 3]). These facts all seem to suggest that the extended wing effect is correlated with the size of the local NRP velocity amplitude and specifically that it is a nonlinearity associated with supersonic velocities. Note in par-

² However, it may be violated for slow rotators with large NRP amplitudes compared to these $V_R \sin i$, e.g., 53 Per. In these stars the NRP velocities at the limbs can change the footpoint of the profile substantially during the cycle.

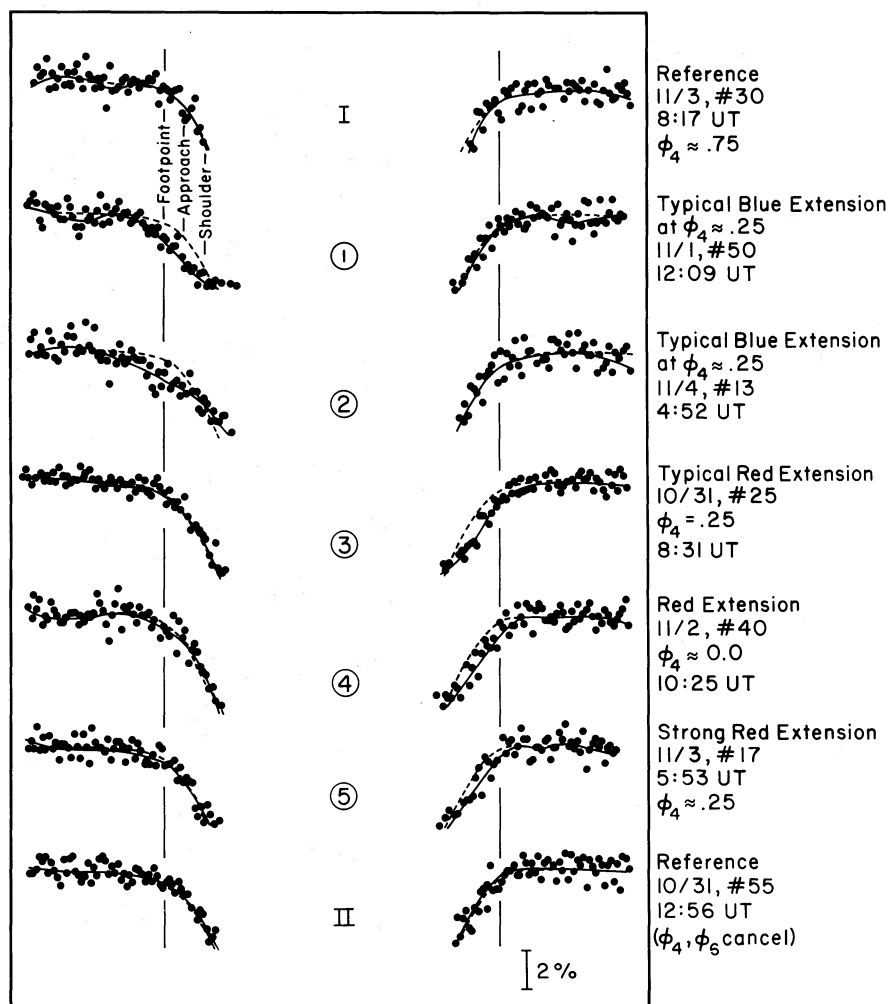


FIG. 1.—Peculiar approaches to the continuum and extended Si III $\lambda 4552$ line wings in ϵ Per, upper portions of the profile only. The upper and lower observations are reference examples and meet the continuum just as a “rotation only” model does (dashed lines). This is not true of the five examples in the middle, which represent most situations. The solid line is a smoothed Fourier fit with the data. The pair of vertical lines are 4.94 Å apart and register the observations in wavelength.

ticular that the $l = 4$ mode has an amplitude of $\sim 15 \text{ km s}^{-1}$, which is probably just subsonic. During constructive interference the $l = 6$ mode adds its velocity. The result is then supersonic, and the extensions are sure to appear. Figure 4 depicts the regions on the stellar disk where the two modes cause blue- and redshifts. Note that at colongitudes of $\sim 70^\circ$ both modes add maximum blueshifts near the “blue” limb and redshifts toward the red limb. Therefore, they require a minimum of help from other mechanisms at these times.

The third and final point to emphasize is that whereas the strongest correlation between extended wings is with the $l = 4$ phase, we observe exceptions to this and all other correlations discussed above, including this one. We believe that any exception for the extended wings must take these “imperfections” into account.

b) Properties of the Modes in ϵ Per

Before analyzing possible causes of the extended wings, it is necessary to give a few results on the NR modes themselves in this star. First, the observations can be explained entirely by a pair of $l = 4$ and 6 prograde, sectorial modes with mean periods of $\sim 3.84 \text{ hr}$ and 2.25 hr . The $l = 4$ mode has the large

amplitude, averaging $\sim 15 \text{ km s}^{-1}$. The $l = 6$ mode averages perhaps 6 km s^{-1} but is much more variable from cycle to cycle. Without “scooping” the results of our later paper, we can state here that the simultaneous photometry of Percy and Fullerton (unpublished) provide unambiguous evidence for these modes being spheroidal. The essential point here is that Rossby or toroidal modes represent *horizontal* waves and are incapable of producing light variations (Smith 1982). On the other hand, the photometric amplitudes have been found to be quantitatively consistent with their spectroscopically derived, vertical-velocity amplitudes. This is not to say that horizontal velocities should not also be associated with these spheroidal modes. Indeed, they should be, and this point will be stressed in the next section.

A second anticipation of our next paper on ϵ Per concerns a result that is consistent with modes in question being sectorial, viz., that $|m| = l$. In particular, the strong beating pattern in one night’s simultaneous photometry and spectroscopy can best be explained by the opposing limb geometries of the sectorial $l = 4$ and 6 modes.

The profile modeling in this paper is accomplished in an identical manner as in Paper I and other papers in this series.

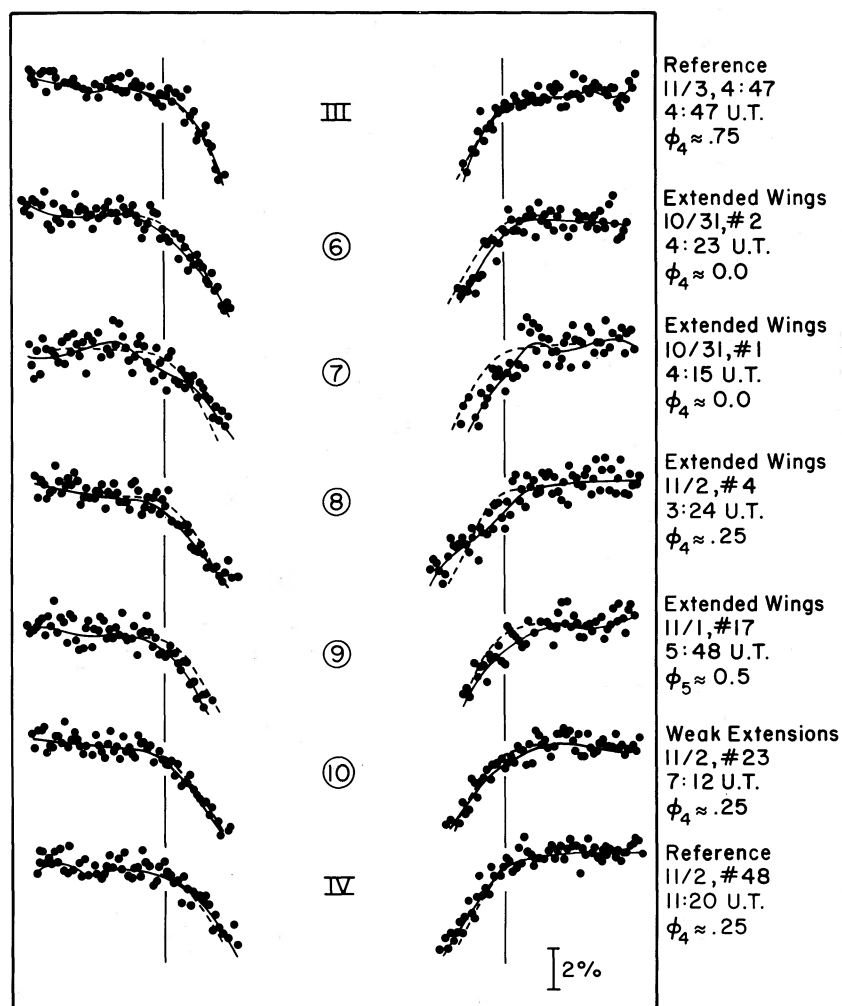


FIG. 2.—Peculiar line-wings in ϵ Per, continued. Same symbols as in Fig. 1. Note the departure of the Fourier-smoothed curve to the dashed line (normal approach to the continuum).

The only important detail to be added is that in our modeling herein we have assumed a stellar inclination of 60° . Actually, there are grounds for believing that this angle is even larger (Paper I). However, we chose this value in case the θ -velocity component in our (r, θ, Φ) polar coordinate system should turn out to produce important line profile signatures. It did not!

IV. UNSUCCESSFUL MODELS

a) Implausible Models

In seeking to understand a new phenomenon, it is often useful to consider a large variety of models, even if some are unrealistic, to get an idea of what types of controlled parameters are important in understanding the observations. We have experimented with computer formulations of several models and summarize the results here briefly. None of them give positive results.

1. *Cycle-to cycle amplitude variations.*—These can produce some fascinating new wiggles in the central section of the line profile but essentially no effects in the wings.

2. *Changes in microturbulence in the intensity model profiles.*—These produce no effect on the wings.

3. *Increases in the line damping or radial-tangential macro-turbulence.*—In principle these could strengthen the wings, but

they do not because they are dwarfed by the large rotational velocity.

4. *Changes in the limb-darkening law.*—These distort the central region of the profile, allowing it to evolve from a quasi-flat, to elliptical, to quasi-circular shape for different darkening coefficients. However, they have very little influence on the wings or line shoulders because of foreshortening and limb darkening itself.

b) Horizontal Velocity Models

Turning from the implausible to more serious models, let us consider the horizontal (θ, Φ) components of the NRP velocity fields and their effects on line profiles. These velocities are expected in nonradial pulsators. Their status is unclear in NRP stars with long periods. In short-period stars their effects on the line profiles are substantial if the ratio of horizontal to vertical velocities exceeds ~ 0.1 . This is roughly the value predicted for the $l = 4$ mode in ϵ Per (the “correct” predicted value of K is slightly ambiguous because of large uncertainties in assigning a stellar radius), and so horizontal velocities should merit careful attention.

The horizontal velocity pattern consists of two components directed in the θ and Φ directions. Both of these velocities necessarily arise because of horizontally directed pressure gra-

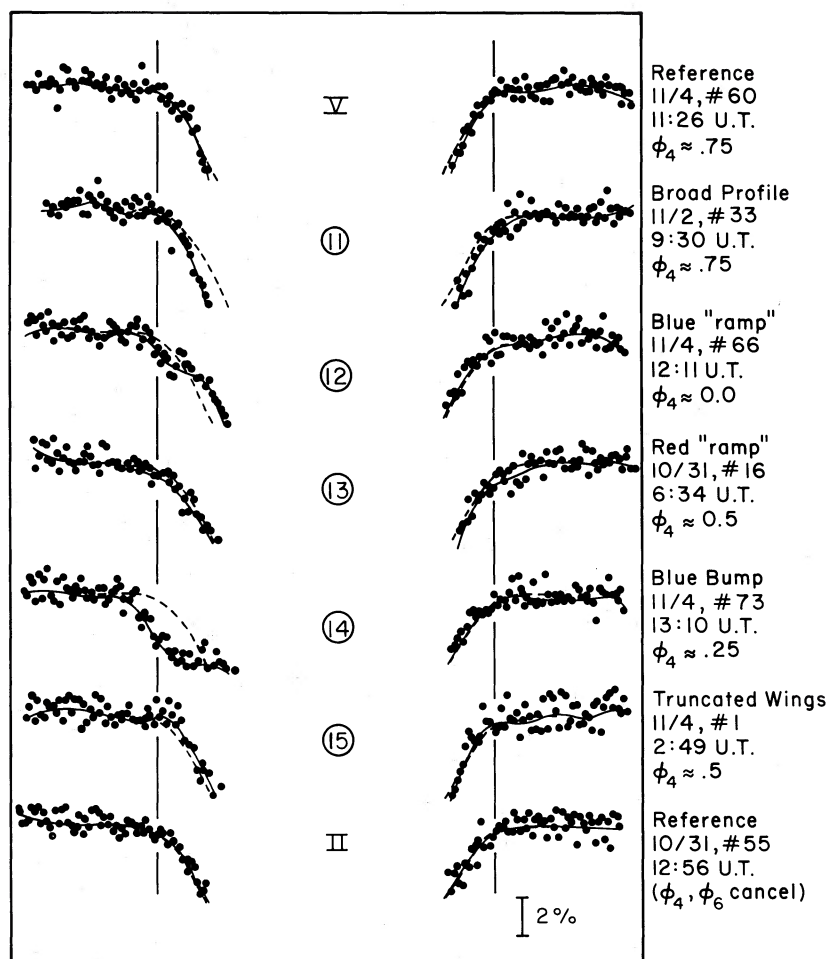


FIG. 3.—Peculiar line-wings in ϵ Per, continued. Note the weak "truncation" of the wings in example 15, a probable measure of the *maximum* of the effect of a competitive mechanism to the shock interpretation (horizontal wave motions).

dients operating on gas elements during the pulsation cycle.³ The specific pressure gradients involved differ for the two components. The θ -component arises because of the slope with θ of the Legendre "envelope", $P^l(\cos \theta)$, which is simply $\sin^l \theta$ for a sectorial mode. The slope with latitude of the isotropic surface is tilted with respect to spherically symmetric surface, and this tilt induces a gradient in pressure and a velocity in the θ direction. This velocity is in phase with the vertical velocity. (The component toward the observer is symmetrical in both hemispheres.) In contrast, the Φ -component arises because of the passage of an azimuthally traveling wave. A test particle feels a maximum acceleration away from a "wave crest" (pressure high) and toward a trough because of the pressure difference between them. After a sustained acceleration, it acquires a maximum ϕ -velocity at the same time it reaches a maximum displacement in θ and r (i.e., when $V_\theta = 0$, $V_r = 0$). Thus, this motion can be compared to the to-and-fro bobbing of a cork in water as a train of waves passes it. The total motion of the particle during a cycle is a closed ellipse which, except at the poles and equator, is inclined to all three coordinate axes.

³ The discussion to follow does not include coriolis effects. One expects the most important coriolis effect to be the creation of a Φ -velocity from the interaction of rotation with the r -(vertical) velocity vector. We have included these Φ -velocities into our modeling using the observed $l = 4$ mode amplitude, and we find them to be negligible everywhere across the line profile.

The line profile signatures of the principal velocity vectors are different, and in principle can be disentangled by following a given wave across the disk. All three create blue-to-red traveling bumps (prograde modes assumed). The interesting difference is that the Φ component produces a strong additional quasi-absorption bump at line center during phase $\phi = 0.75$. It also produces a steep inner line shoulder followed by a shallow approach to the continuum. The θ -component can be distinguished from the r -component through its slightly different dependence on latitude or through more discernible differences at low observer-inclinations. What is important in the present context is that the θ -component velocities are always small or zero near the equatorial limbs. Because we are concerned in this paper only with the far wings of the profiles, which are formed at the equatorial limbs of the stellar disk, we can drop the θ -component from consideration. However, the Φ -component is another matter. This component shows significant influences on all *but* the central portion of the line profile. At $\phi = 0.25$, the principal phase of interest, a combination of r and Φ components produces W -shaped profiles with weakly contrasted bumps, as well as a broadened inner profile. These features are generally not observed in NRP stars, and therefore it has been possible in the past to set stringent limits on horizontal velocities (upper and lower limits, for short- and long-period stars, respectively). For the sake of argument let us

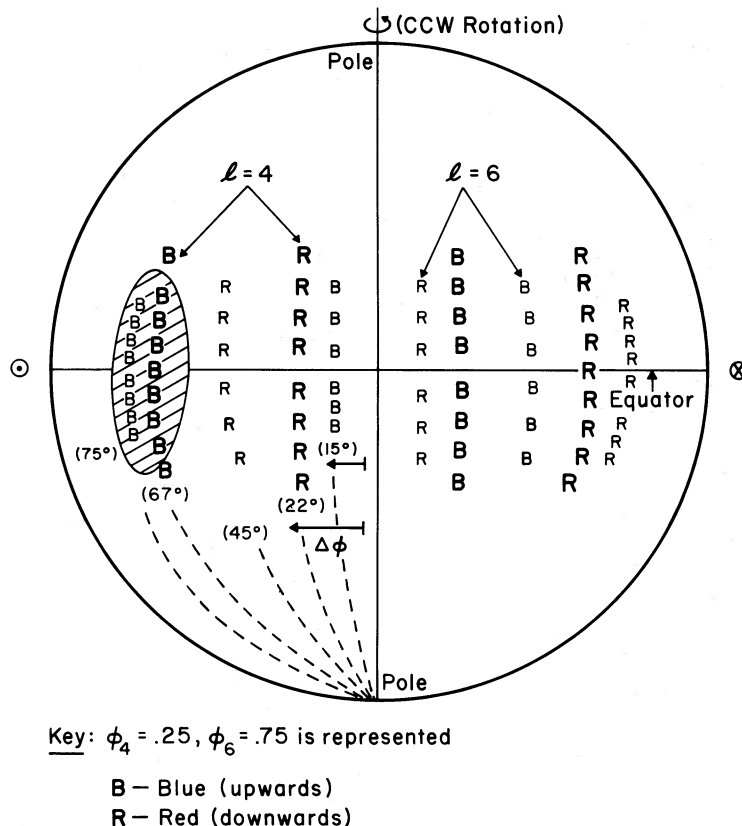


FIG. 4.—Schematic model stellar disk, viewed equator-on. The “R” and “B” symbols designated *blue*- and *red*shifted areas, respectively, on a star having two nonradial modes with $\phi(l=4) = 0.25$ and $\phi(l=6) = 0.75$.

assume a model in which horizontal velocities exist in the atmosphere of ϵ Per with a strong vertical gradient. (We set aside temporarily the question of whether this gradient could be maintained against shear instabilities.) Then in such a model the observer could “see through” the large Φ -velocity fields in the central region of the stellar disk and examine their influence only near the limbs where they would affect the line wings. When one implements this type of velocity field in a line profile-generating program, one finds the following results. First, at $\phi = 0.25$ the behavior of the far blue wing and line shoulder are each altered significantly, and in different directions! The far wing is extended at this phase, but it is so shallow that it would probably be imperceptible in actual data. In contrast to this behavior, the line shoulder goes “into weak emission,” although not above the continuum. (Certainly no weak emission is observed in the great majority of cases.) At $\phi = 0.5$ the shallow, extended wing feature deepens, which is “good,” but the line shoulder then goes into even stronger emission, again not observed. What is also not observed at this phase is that the opposite (red) wing in the line is predicted to become strongly truncated (just as the blue wing is supposed to become truncated at $\phi = 0.0$). Finally, at phase $\phi = 0.75$ the entire line shoulder is in absorption, and the far wing has a remnant of absorption as well. The only problem with this last point of success is that it is the wrong phase! In fact, only on rare occasions are wing extensions ever seen at $\phi(4) = 0.75$. The important upshot of these details is that it is not permissible to save the horizontal velocity model by introducing an arbitrary phase shift into the Φ -velocity field. These velocities must be constrained to follow the specific pressure gra-

dients referred to above. Therefore, even vertically stratified, horizontal velocities that adhere to a spheroidal mode description do not match the detailed observations of when the line wing extensions occur, as well as the general absence of truncated wings at other phases.

So far in this discussion the observed wing extensions usually *cannot* be explained by horizontal motions accompanying spheroidal modes, even in the best case in which a (probably) unreasonably large vertical shear is postulated. Still, we do believe that occasional anomalies that have been noted can be attributed to time-variable horizontal motions associated with the two spheroidal modes. We have in mind certain times of constructive interference between the $l=4$ and $l=6$ modes leading to a pair of strong extended wings at $\phi = 0.75$ (example 11, and possibly at 7:30 UT on October 31). This is indeed the phase for which the spheroidal Φ -velocity model predicts a pair of strong wings. Planimetry of the example 11 profile does not show an increase in line strength relative to profiles observed an hour earlier and later on that night, implying that no differential motions are present along the line of sight. These considerations suggest that Φ -velocities are the correct candidate diagnosis in this case. In addition, they are probably essentially depth *independent*, so that one does not have to be concerned with the maintenance of strong vertical shears.

A few other loose ends remain. The first is the consideration of Rossby waves and related toroidal modes. Sectorial Rossby waves can be eliminated quickly because the Φ -velocities are zero all along the equator. In any case, the close correspondence of the extended wings to the presence of the $l=4$ mode

already hints that they are related to this mode's *spheroidal* nature. The second loose end is the consideration of tesseral modes, with $|m| < l$. We have independent evidence from "modal commensurability" arguments (see Paper I) that the $l = 6$ mode is sectorial, but we have no independent evidence that this is true for the $l = 4$ mode. Therefore, we consider the Φ -velocities from a postulated $l = 5$, $m = -4$ mode. We discovered the effects of these velocities are inconsequential in the wings of model profiles. The reason for this is that the Legendre function for this mode is $P_m^l(\cos \theta)/\sin \theta = \sin^3 \theta \cos \theta$ and is therefore zero near the equator, just as we had found for the Rossby waves. We conclude that if the mode is indeed spheroidal, as implied both from line profile signatures and photometry, then the line wings can be most easily influenced by sectorial modes. Therefore, we discard the tesseral modes from consideration in the present context.

A third loose end is the matter of the truncated wings in example 15. This feature arises at the "right" time, $\Phi \approx 0.5$, for it to be caused by Φ -velocities associated with spheroidal modes. Yet if this is the case, why do truncated wings fail to appear at other times when the $l = 4$ mode has this phase? We believe that the correct answer to this question is that this epoch also corresponds to $\phi(6) \approx 0.5$, which is the phase for which the shoulder develops the most quasi-emission. Thus one can expect that this occasional alignment in phase has produced about as strong an "emission shoulder" as these two modes together are capable of producing. If this explanation is correct, it implies that under ordinary circumstances the effects of Φ -velocities on line shoulders are generally just below the detection threshold. However, at least we may finally have a tangible example that will allow us in the future to quantify the horizontal velocity effects that we have been expecting for so long.

Returning briefly to the basic question of whether *any* type of horizontal motion can reproduce the extended wings, let us finally consider Φ -velocities which, like a terrestrial jet stream, never reverse themselves. This family of velocity fields is very easy to dismiss for the extended wing effect because the observations demand a good correlation with $\phi(4)$. Yet any jet stream initially in phase with a particular $l = 4$ wave crest would soon drift out of phase, producing extended wings at random times. We have also considered Φ -velocities associated with waves that drift azimuthally relative to neighboring waves in the pattern. It is easy to dismiss these models for the general effect as well, basically because the drift velocities required are large enough to cause unobserved, random phase irregularities from cycle to cycle. Although phase *nonuniformities* are observed in ϵ Per and other stars occasionally (Smith 1985*a, b*, 1986), they tend to be repeatable each super period (i.e., the cycle-to-cycle period times m) and not random in occurrence. In addition, those irregularities that are observed in ϵ Per do not generally correlate in time with the appearance or with abnormal strength of extended line wings. However, there is a single exception to these generalizations, represented by example 14. That example shows "extra" absorption both in the blue shoulder and blue wing of the line. As will be discussed in our next paper on ϵ Per, $\sim 1\frac{1}{2}$ days before this particular observation was made an "impulsive event" occurred in this star. This event injected energy into certain cycles of both modes, and in doing so spread the neighboring wave crests apart from each other. We speculate that the appropriate wave crests for both modes were relaxing back to their former positions when example 14 was observed (the particular cycles

involved and the directions they must return to are both correct for this to have happened). This relaxation would create an additional blue velocity near the approaching limb of the star and create absorption out to and beyond the blue footprint in the line profile. Thus, it is possible that this type of transient, azimuthal velocity field could be responsible for the generally broadened profile noted in example 14.

In summary, of the many extended line wing events observed we are able to attribute perhaps two of them (examples 11 and 14) to a Φ -velocity field associated with the spheroidal modes or with a disruption to these modes. A spheroidally induced horizontal velocity field may also be responsible for weak quasi-emission, in the shoulder(s) at one other time (example 15). A small part, but not even most, of the wings (for then we would have regular and equally strong red wings) could come from the raised bulge which appears over the stellar limbs at $\phi(4) = 0.25$. Otherwise, the effects of horizontal motions from *any* cause appear to be marginal or unobservable in the atmosphere of ϵ Per.

V. THE ATMOSPHERIC-SHOCK, LAWN-SPRINKLER MODEL

a) Justification of the Model

Certain details in these observations of ϵ Per, such as the rapid strengthening of the extended wings, their occasional "ramplike" appearance, and the increase in line strength are common features in spectra of large-amplitude, radially pulsating stars, according to Willson and Bowen (1985, hereafter WB). These authors stress that shocks are the inevitable consequence of a sinusoidal wave passing through an atmosphere of decreasing density. The stronger the subsurface velocity amplitude imposed, the deeper in the atmosphere the wave will develop nonlinearities and take on shock characteristics. Unlike the situation on the surface of a single-shocking supernova, the atmosphere of a pulsating star adjusts to the dynamical pressure imposed by regularly spaced shocks. Then one expects roughly the same observational signatures to occur at appropriate phases of each cycle.

Shocks are thought to occur in the related class of β Cep stars (Smith 1983). The shocks are observable in visual or UV line profiles of every star for which a search has been made. One finds that even small amplitude pulsators (e.g., γ Peg; pulsational amplitude = 5 km s^{-1}) show shock attributes in their spectra. This observation should not be surprising since the shock strength is only a weak function of pulsation amplitude (WB). As stated already, both line profile and photometric observations of short-period pulsators like ϵ Per indicate that the pulsational velocities are overwhelmingly vertical. Therefore, locally a gas parcel should respond to a passing wave in the same manner, no matter whether the wave propagates vertically or azimuthally: the essential point is that in both cases the parcel is accelerated *vertically*. This logic has led us to predict (Smith and Penrod 1985) that shocks should exist in nonradial pulsators as well as in radial pulsators. The only differences are in the area on the stellar disk affected and their timing. In an NRP star shocks will be confined to the near-equatorial regions, where the $\sin^l \theta$ amplitude factor is large, and they will occur *sequentially* around the star's equator rather than over the entire area only at one phase. Consequently, at any instant the effect should be small. If shocks are to be observed in an NRP star at all, they should be detected most easily in one with a large pulsation amplitude, a high inclination, and a low- l mode. From these considerations it should be

expected that ϵ Per is a prime candidate for exhibiting the strongest shock signatures. Still, some of these parameters (e.g., amplitude and l -value) only weakly affect the appearance of these signatures, and therefore careful observations of other stars should turn up a similar phenomenon.

What are these signatures? In β Cep stars one observes transient absorption features typically in a preferred wing (although occasionally in both) during two phases of the cycle, just before maximum compression and ~ 0.3 cycles later, i.e., just before and during radial velocity minimum (Smith 1983). The current interpretation is that each of these two events is caused by a separate shock passing through the line formation region during the pulsation cycle. The shock may manifest itself either in the blue wing (e.g., γ Peg) or the red wing (σ Sco, ν Eri), or both, depending on the details of the shock amplitude and its optical depth. The UV line data uniformly show pronounced blue wings associated with the *second* event, at radial velocity minimum. Then in our picture it is reasonable to assume that a depressed blue wing is produced during the atmospheric expansion, i.e., from those regions on the stellar disk showing blueshifts. Likewise, if γ Peg is a good guide, it is logical to expect a somewhat weaker, extended red wing ~ 0.6 cycles later. These features can be seen best when they "clear" the rotational profile, i.e., beyond the profile footpoints. They would appear when the combined blue or redshifts from the shock and rotation achieve a value in excess of $V_R \sin i$. In β Cep stars the inferred shock amplitude varies as $\sim 24/17 \times 55 \approx 80 \text{ km s}^{-1}$ in γ Peg, to 130 km s^{-1} or more in large-amplitude pulsators. We will take 100 km s^{-1} as a typical number and apply it to ϵ Per. This star has a $V_R \sin i = 134 \text{ km s}^{-1}$, so that one can expect that an extended blue wing feature should arise from elements near the stellar equator and rather closer to the limb than the substellar point. According to our description of the wing phenomenon [and in particular, with emphasis on the importance on those times when $\phi(4) = 0.25$ and $\phi(6) = 0.75$], we infer that the disk elements responsible for the wing come from the colongitudes of $\sim 67.5^\circ$. Then, consulting Figure 4 again, one can imagine shocks at this colongitude blueshifted by $100 \times \cos 67^\circ = 38 \text{ km s}^{-1}$. This figure corresponds nicely to the 40 km s^{-1} extension of the wing beyond the footpoint usually observed. Therefore, the shock hypothesis matches the observations both in terms of the predicted velocity and times of occurrence. The horizontal velocity fields were not able to do this!

There are two other important agreements of the shock model. First, by analogy with the shocks observed in β Cep stars one can expect one of the wings to show a stronger absorption than the other. Second, our picture does not really require a strict repeatability with $\phi(4)$. Shocks in β Cep stars also show some lack of repeatability. In addition, this mechanism relies upon the creation of supersonic nonlinearities at appropriate phases between the two traveling waves. An appropriate analogy to our picture might be the observation of "white caps" on ocean waves from an airplane. At any given moment the white caps will occur in only a small number of apparently random places and almost never quite the same way twice. On an NRP star the "white caps" move smoothly along the equatorial belt with instantaneous fluctuations arising from mode interferences. From the combined Doppler component of a $\sim 100 \text{ km s}^{-1}$ shock and 134 km s^{-1} rotation, one can predict that a maximum strengthening of the extended wing should occur somewhat after $\phi(4) = 0.25$, perhaps at $\phi(4) = 0.35\text{--}0.40$. Both of these predictions also agree with the

observations. Finally, one should see the extended wings like the white caps, to some degree virtually all the time, and indeed this, too, is the case.

The final plausibility test of the lawn-sprinkler model comes from asking whether it is strong enough to be observed in photospheric absorption lines. To investigate this, let us start again with the β Cep stars. Shocks in these stars seem to be responsible for large variations during the cycle (Campos and Smith 1980; Smith 1983). At the low-amplitude extreme, the Si lines of γ Peg vary with a total amplitude of $\sim 22\%$. The corresponding variability in ν Eri lies in the range of 50%–70%! Then we will take 25% as a representative figure and apply it to ϵ Per, after making proper allowance for the area on the star that can show "white caps" at any one time. To formulate this areal estimate, we will assume that shocks arise whenever the local pulsational amplitude is at least $\frac{1}{2}$ the maximum amplitude along the wave. For an $l = 4$ mode this admits latitude limits of $\pm 33^\circ$, or 54% of a longitude belt if the star is viewed equator-on. In like manner, the longitude limits are one-third of a cycle, or one-sixth of all the longitudes across the disk. Then the predicted variation in line strength should be $\sim 0.25 \times 0.54/6 \approx 2\%$. This is in precise, and probably fortuitous, agreement with the observations.

In summary, all of the quantitative tests that we are able to formulate, namely, the frequency, timing, and the maximum velocity extent of the wings, as well as the variation in line strength it causes, all conform to what we are able to borrow from the comparatively well-observed examples of shocks in β Cep star atmospheres. With the exception of a very few events noted in the last section and attributed to horizontal Φ -velocities near the limbs, we believe it is possible to identify unambiguously the lawn-sprinkler shock process as that responsible for the extended line wings in ϵ Per.

b) Influences of the Shocks on the Circumstellar Environment?

Epsilon Persei is thought to be luminous enough for its radiation pressure to initiate a continuous, stellar wind, and this wind has been observed (Snow and Morton 1976; Lamers 1981). The results of this paper provide support for the view that some pulsationally driven mass loss can occur from all NRP stars.⁴ However, this rate is not necessarily large. Burger *et al.* (1982a, b) and Blomme and Hensberg (1985) estimate modulations of 50% or less for BW Vul and σ Sco, over and above the steady state radiative wind rate. Given an $l = 4$ mode in ϵ Per, one can expect that this star has a mass-loss rate of about one-fourth that of a β Cep star with a comparable period and amplitude, i.e., $\sim 10\%$ if present estimates are to be believed (note that a higher mass-loss rate has been estimated for ϵ Per than for BW Vul!). Obviously, this figure does not represent a great addition to the steady wind, and it will have little *direct* influence on the circumstellar environment. Perhaps more important than modulating the steady mass-loss rate is the potential role of these shocks in imposing a ready-made instability into an otherwise quasi-steady flow. Lucy and White (1980) and Owoki and Rybicki (1985) have suggested

⁴ We ignore here impulsive events associated with nonradial pulsations, one of which is documented for ϵ Per in a forthcoming paper in this series. These events are probably the optical counterparts of the "puffs" discussed by Gry, Lamers, and Vidal-Madjar (1984). No one has been fortunate enough yet to follow the material associated with these puffs outward to see whether it escapes the star. We suspect it does (see Peters 1986) but cannot be sure yet. If so, the mass-loss rates caused by NRP would be significantly raised over the "steady state" estimates in our text.

that small-amplitude instabilities introduced into the acceleration region of a stellar wind can grow to such large amplitudes that X-rays will be produced by local, radiatively driven shocks. We conjecture that nonradial pulsations introduce periodic local perturbations of 10%–40% in the density of the wind and that these perturbations serve to “seed” these radiative instabilities. The combination of short periods and high- l geometry associated with NRP in OB stars is well suited for producing instabilities for flows in *any* direction (including polar). The time scale for changes in the local velocity field is

probably of the order of 5×10^2 – 10^3 s, which is much shorter than the expansion time scale of the wind and close to the natural amplification time scale of the wind ($\sim 10^2$ s; Owoki and Rybicki 1985). It will be of interest in the future to attempt to correlate fluctuations in X-ray flux with the periods, degrees, and amplitudes of NR modes in early-type stars.

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MYRON A. SMITH: National Solar Observatory, Box 26732, Tucson, Arizona 85726