# TOWARD A MODEL FOR THE Be BINARY SYSTEM φ PER

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**Abstract.** Arguments are presented against the adoption of an early B-red giant combination for the φ Persei system. Velocity curves of the primary and secondary components based on the measures of the He I lines on nearly two hundred plates are shown and discussed insofar as orbital parameters and system membership are concerned. Evidence from the He I lines, the emission edges, shell absorptions, and underlying wide absorptions of the hydrogen lines indicate that the system is made up of a B1 primary and a B3 secondary, both of which are emission-line stars.

## 1. Introduction

Interest in the star φ Persei – which lay largely dormant since the papers of Hynek in the 1940's (Hynek, 1940, 1944) – has recently begun to emerge again among investigators of the Be and shell phenomenon. This enigmatic star exemplifies in many ways the problems which beset astronomers studying these types of stars – namely, it is a spectrum and radial velocity variable. Its variations occur periodically in the space of some 127 days and strongly suggest that the system may in fact be a binary.

## 2. Discussion of the B-Red Giant Hypothesis

Recently, Plavec (1975a, b) and others have advanced the hypothesis that a tentative model for the φ Persei system might consist of a main-sequence B0–B1 star and a hypothetical red giant companion, presumably of about spectral type K, which would transfer matter to a shell or ring about the earlier primary through the inner Lagrangian point. It is based largely on the failure to find evidence for the presence of a B type secondary star in the far ultraviolet *Copernicus* scans and the hypothesis advanced by Kříž and Harmanec (1975) among others that probably all Be and shell stars are interacting binaries.

   Although this author has not had access to the *Copernicus* data of Plavec, he states that two ultraviolet observations were made, one of these being the more relevant to test for duplicity, namely the one *Copernicus* scan made at second quadrature phase. At this phase according to my model (Hendry, 1975) which suggests that the system consists of a B1 primary and a B3 secondary, the predicted separation of the lines from the two components is about half an angstrom at λ 1200 Å. Since the resolution of the *Copernicus* scanner is at best about 0.2 Å in the relevant scanning mode, the separation of two even moderately rotationally broadened photospheric lines would clearly at best be extremely difficult. Observations in the higher dispersion *Copernicus* scanning mode were, by circumstance, limited to sharp interstellar lines and can not support or contradict duplicity. Also, if one considers the hypothetical spectral type of the secondary star to be B3 as my model would suggest, and the observed spectral type of the primary to be B1, calculations show that the secondary

would be from 1.5 to 2.0 mag. fainter at $\lambda$ 1200 Å, and consequently, would be unlikely to be easily visible. Therefore, the observations in the far ultraviolet do not contradict a model containing two B-type stars since the model does not predict the secondary spectrum to be easily visible in this region of the spectrum, and even if it did, one might hesitate to destroy a model based on 184 observations which seems satisfactory in the photographic and infrared on the basis of a single observation.

But let us accept for the moment the ad hoc assumption of a late-type companion within the system. On this basis, one would expect, first, to find several predicted features in the photographic and infrared – which are not observed – and secondly, one should also expect that the B – K model would explain certain features which are definitely observed on the strength of nearly two hundred plates. Neither of these expectations appears to be fulfilled. The spectrum of $\phi$ Persei has been examined in the photographic infrared for any evidence whatsoever of the existence of a late-type companion and no trace of such a star was found. Furthermore, artificial composite spectra were made of a combination of a B-type star and a K-type star with different relative exposures so as to simulate increasing magnitude differences between the two stars. It was found that the K-type star would have to be nearly three to four magnitudes fainter in the infrared than the B-type star for it to be invisible in the spectrum. Therefore, unless greatly underluminous or the primary overluminous by some three magnitudes, the late type star should be visible in the infrared spectrum of $\phi$ Persei if it exists.

Evidence of the late-type secondary can also be searched for at still longer wavelengths from 2.3 to 19.5 $\mu$. Such observations have been made by Gehrz *et al.* (1974) and they found that indeed $\phi$ Persei does have an infrared excess. However, this excess is well-fitted by a purely free-free radiation model from proton-electron scattering in a hot ionized circumstellar plasma. Of course, the excess could be explained by a cool infrared companion. Nonetheless, from Kepler's Law, the center of mass separation between the primary in the $\phi$ Persei system and the hypothetical infrared secondary is only about 1.5 AU, far too small for the short wavelength flux of the B-type star not to seriously affect the secondary's photosphere.

## 3. Observations

The B-red giant model can not satisfactorily explain the observations upon which my model of two B-type stars is primarily based. The model is based upon measures of 184 plates of various dispersions from Mt. Wilson, Perkins, Michigan, David Dunlap, and Northwestern's observatories. Measures of the spectral features of $\phi$ Persei are somewhat difficult; that is undoubtably why the star holds second place only to Algol in the number of spectrograms taken of it. The paradoxical out-of-phase behaviour of the dominant (and I stress the word dominant) component of the doubly-structured helium lines has been fully confirmed by my recent measures, as has a double periodicity in the velocity curves of the emission edges of the hydrogen lines.

Some doubts have been raised concerning the visibility of these helium lines from the secondary component. I was not the first to see them; they were first measured by

Whitt, later by Hynek (1944), and most recently oscilloscopically by Hickok (1969). Further, the precaution was taken in the measures of not calculating phases until after the radial velocity reductions were completed. This procedure was scrupulously followed so as not to bias the measurements. Clearly, then, we do not have a 'Martian canal' situation.

It has also been suggested that with spectral types of B1 and B3, the secondary star would be nearly invisible in the spectrum of the dominant primary. Calculations show that in the photographic region the magnitude difference is about 1.1 mag., difficult but not impossible to discern, as is evidenced by the work of Batten (1962) on V380 Cygni, Popper (1943) on V Puppis, Pearce and Plaskett (1932) on 57 Orionis, and Petrie (1950) on BD +58°2546, where similar magnitude differences and spectral types are involved.

The results of the measures of the helium lines are shown in Figure 1. The measures have not been formed into normal points on the graph so as to indicate the scatter of individual measures more clearly. Measures near the $V_0$ axis have been purposefully omitted as subject to a high degree of blending and hence, unreliable. An orbital solution was performed on the primary and secondary star velocities separately using a version of the program of Wolfe *et al.* (1974). The derived orbital elements appear in Table I. The individual masses of the stars are found to be 15.0 and 8.2 solar masses, respectively, if an orbital inclination of 80° is assumed, a not unreasonable assumption from the appearance of the spectrum and the absence of
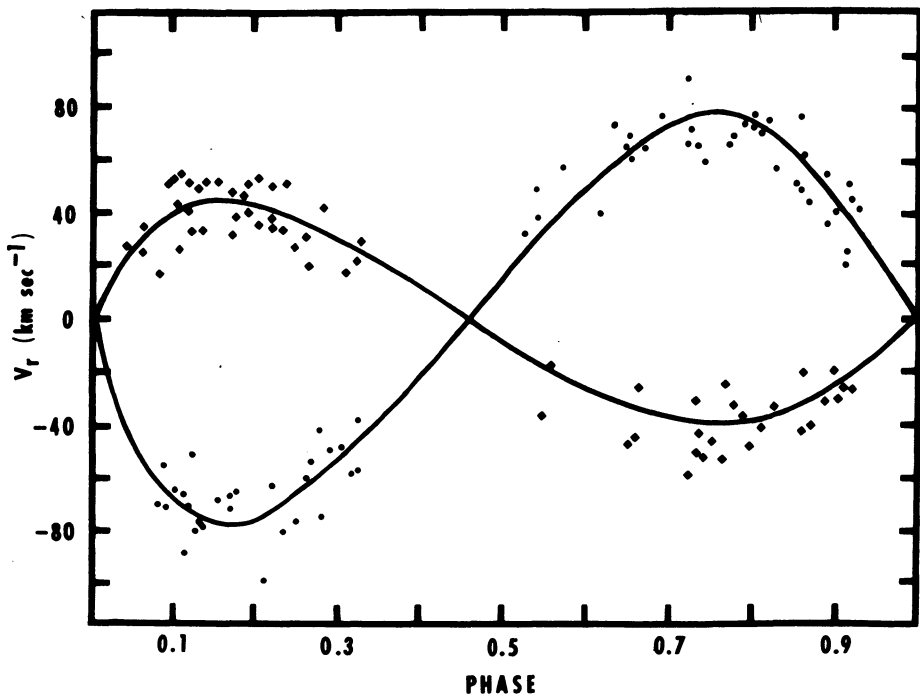


Fig. 1.   Velocity curves derived from measures of the lines of He I. The solid lines denote the curves of the orbital solution.

TABLE I

Orbital elements of the $\phi$ Persei system

$P = 126.696$ days
$K_1 = 42.5 \pm 4.1$ km s$^{-1}$
$K_2 = 77.5 \pm 3.5$ km s$^{-1}$
$V_0 = 0.0 \pm 3.0$ km s$^{-1}$
$e = 0.15 \pm 0.02$
$\omega_1 = 285° \pm 15°$
$a_1 \sin i = 7.3 \times 10^7 \pm 0.2 \times 10^7$ km
$a_2 \sin i = 1.3 \times 10^8 \pm 0.2 \times 10^7$ km
$M_1 \sin^3 i = 14.28 \pm 0.3$ solar masses
$M_2 \sin^3 i = 7.82 \pm 0.3$ solar masses

eclipses. Curiously, the helium absorption lines of the primary are the more difficult to measure since they are more rotationally broadened and the lines of the secondary are never completely free of the blending effects of the primary. Hence, the values of $K_1$ and $K_2$ found are mimimum estimates and that of the mass ratio, a maximum estimate.

However, an immediate question arises. Measures of the $v \sin i$ of $\phi$ Persei have indicated very high values. Consequently, measures of duplicity in such a system where at least one of the stars is rapidly rotating and has wide profiles are suspect. Yet, tracings of $\lambda\lambda$ 4026 and 4471 Å of He I show duplicity clearly with the component from the secondary star being sharper and more intense. This is an
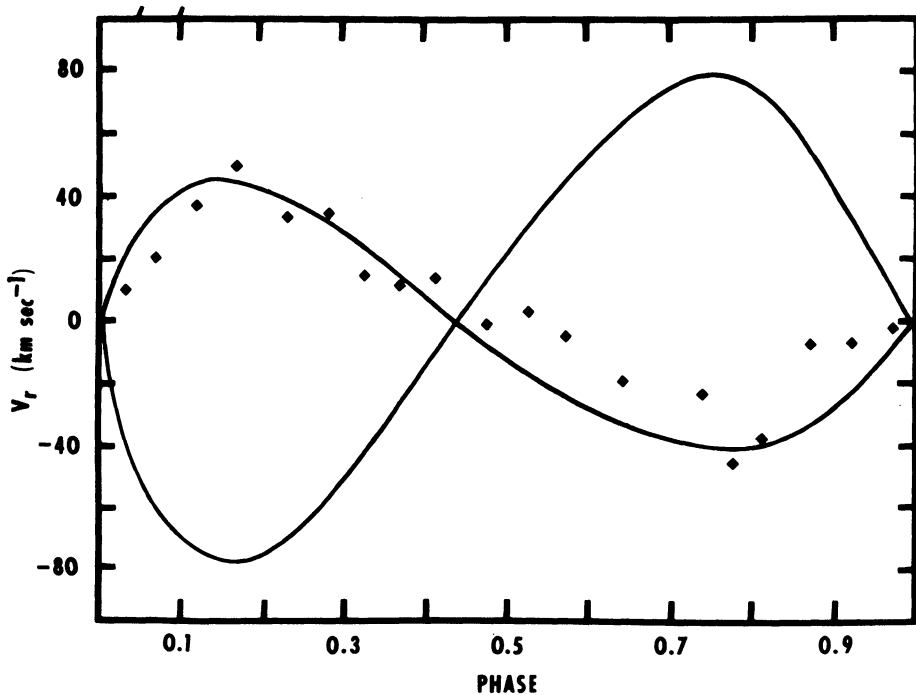


Fig. 2.   Velocity curve derived from the measures of the sharp Balmer curves of the primary. The solid lines denote the curves derived from the orbital solution.

important point: as is evidenced by both the recent measures and those of Hynek and Whitt, the primary contribution to the He I triplet lines is from the secondary star. This is nearly impossible to explain by a hypothesis that emission in the lines or some such other feature could mimic duplicity. Also, corroboration of the existence of a B-type secondary comes from the measures of other features in the spectrum. Very infrequently on only the best plates, lines of other ions such as N II, O II, Si II, and others are seen and measured. These lines follow the secondary's velocity curve exclusively which is consistent with the secondary being a more slowly rotating B star.

The velocity curve derived from the measures of the sharp Balmer cores appears in Figure 2, superimposed on the theoretical curves of the orbital solution. It can be immediately seen that it is probably non-Keplerian and shows the influence of gaseous motion within the system. The points plotted are the means of individual observational points and in this process of forming the normal points, the quite considerable scatter for such sharp features is masked. The scatter is in part intrinsic, as might be expected since the lines are clearly formed in the shell of the primary, and is also a function of the asymmetry of the lines which becomes quite marked at certain phases, thereby making visual measures subject to uncertainty. The form of the hydrogen curve is not entirely definitive, however, since it is derived from measures of plates taken from 1925 to 1975 and there is some evidence that the form of the curve undergoes slight secular changes. This point is still under investigation. However, it may be mentioned that the helium lines and the lines of the other elements used for the orbital solution show no evidence of any secular change from cycle to cycle or of non-Keplerian motion.

The behaviour of the hydrogen lines also suggests that the secondary star is an early B-type star. The structure of these lines is quite complex and is made up of the following contributions: (1) Wide underlying absorption from the primary (2) Wide absorption from the secondary (3) Intense shell absorption from the primary (4) Weaker shell absorption from the secondary (5) Strong double emission from the primary (6) Narrower double emission from the secondary.

Evidence for the contribution of the wide underlying hydrogen absorption of the secondary star to the line profiles of the primary is found both in examination of the profiles themselves and in measurements of the velocities of the absorption edges. The wing of Hδ is definitely displaced to the violet of the sharp core when the core is at maximum positive velocity and vice versa when it is at negative velocity. The widths of Hδ are found to vary such that the line is widest at both velocity maxima and narrowest when the curves are near to the systemic velocity. This is consistent with the blending hypothesis.

The presence of the central shell absorption of the secondary can be directly seen. On the best plates, there appears to be a second sharp and faint absorption core between the wing and the central sharp Balmer core of the primary which is nearly coincident with it, producing observed asymmetries except at the velocity maxima when it is separate. Measures of this secondary core agree in direction and approximate magnitude with the theoretical curve of the secondary star, and consequently, can be expected to be formed from the projection of shell material onto its photosphere.

That the secondary star possesses also double hydrogen emission lines can be seen in the behaviour of the primary's emission lines. At about phase 0.2, the violet component of the emission line is observed to be wider than the red component, while the central absorption becomes diffuse and 'filled-in'. This can be accounted for by the presence of the secondary's double emission line. Its violet component is velocity-shifted so as to artificially broaden the primary's emission profile by superposition and the secondary's red component acts to fill in the core, and hence causes it to appear more diffuse. At about phase 0.7, the opposite effect occurs and it is the primary's red emission which is widened and the core is once more filled in. This effect is corroborated by the velocity measures of the emission edges of hydrogen. The curves obtained from the measures of the emission edges of hydrogen are illustrated in Figure 3. The absolute values of the measures are not important but the forms of the curves are. Presumably, approximately the same point on the profile is measured each time. A double-peaked curve of unequal amplitude is found and
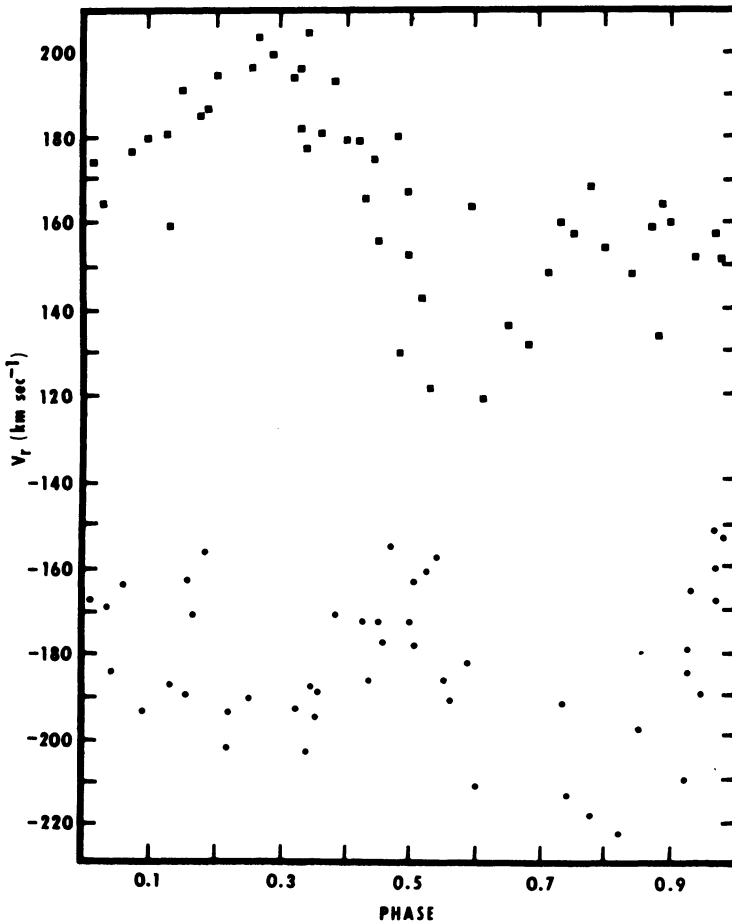


Fig. 3. Velocity curves derived from measures of the emission edges of the hydrogen lines Hβ through Hδ.

seems consistent with the superposition hypothesis. The primary's emission may be surmised to be wider; at the first quadrature phase it extends further to the red. At this phase, however, the violet edge is not extended as much by the secondary's contribution. The situation is reversed at the second quadrature phase. Consequently, it may be seen from the evidence of the hydrogen emission that the secondary star is also a Be star with its own concomitant shell.

A brief note on the behaviour of the other features in the spectrum in view of the proposed model is in order. The H and K lines of Ca II follow a velocity curve which is essentially that of the primary but with far smaller amplitude. This may result from a blending of the components of both stars and their shells and this is corroborated by the occasional doubling seen on good plates, measures of which confirm that one component essentially follows the primary and the other the secondary. The central absorptions of the Fe II lines in the photographic and the infrared follow much the same behaviour and may also be composite. Their emission edges mimic the double periodicity of the hydrogen emissions and presumably the same explanation of a contribution from each shell applies. Measures of the central absorptions of the infrared Ca II triplet lines, whose emission edges are blended to different degrees with the Paschen emissions and which were made from considerably lower dispersion plates than the rest of my data seem to indicate that these lines follow the primary and their emission edges do not reveal the influence of any emission from the secondary. Clearly, the conditions under which they are formed seem to be unique to the primary and its shell.

## 4. Conclusions

The observations then seem to indicate that the $\phi$ Persei system is made up of two Be stars, each with a shell whose properties or interactions causes the distortions in the velocity curve of the Balmer lines. To state more than this at the present time would be premature and a more quantitative description of the proposed model is under study at the present. However, it would seem that the adoption of a B-red giant combination, although tempting from a theoretical point of view, is somewhat arbitrary and not in agreement with certain of the observations.

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# DISCUSSION

*Cowley:* Can you make some estimate as to what the individual masses are and what the sizes of the stars are, with respect to the Roche lobes?

*Hendry:* From my preliminary orbital elements I find a mass ratio of about 0.55 and if I assume an angle of inclination of about 80° for the system it gives me masses of about 14.3 and 7.8; something like that.

*Cowley:* What is the period of the system?

*Hendry:* 126.696 days.

*Cowley:* OK. That means that neither star comes close to filling the Roche lobe. They are two separate stars. So that if we are talking about binary stars, we are not talking about mass transfer.

*Hendry:* That's correct.

*Polidan:* (1) Regarding the detection of the K-type star, we also have formed composite spectra and we find great difficulty in seeing the late type star's lines if the *I* magnitude difference is greater than roughly 2.$^m$5. If indeed $\phi$ Per does have a K-type companion we expect that it would have a greater magnitude difference than this. It could possibly be as large as three to four magnitudes in *I*.

(2) As for the Ca II core, from our higher dispersion data we find that because of the severe blending of the nearly equally strong Ca II and Paschen lines (Ca II peak = 1.38, Paschen peak = 1.25; see Figure in my talk) that it is impossible to measure the true core of the line. One must remove completely the Paschen emission line to see the true reversal in the calcium line.

(3) Regarding the far infrared flux of $\phi$ Per, as I pointed out in my talk, it is impossible to distinguish between free-free emission and a K-type continuum in the region beyond 2 $\mu$. Swings and Allen (*Publ. Astron. Soc. Pacific* **84**, 523, 1972) pointed this unfortunate fact out. Combining this with the expected small flux contribution of the K-type star, it is not surprising that no obvious evidence of a cool secondary in $\phi$ Per exists.

*Hendry:* In response to your comments (1) In my artificial composite spectra (B plus K), the spectrum of the B-type star with a K-type spectrum added with a 4-mag. difference in *I* didn't look like a B-type star; it looked anomalous. On that basis, I am saying that one could possibly see evidence of a K-type component almost four magnitudes down, as was predicted by Hynek in his study of composite spectra.

(2) My Ca II emission peaks are very high and the Paschen peaks are reasonably low above the continuum. The difference in wavelengths between the Paschen lines and the relevant calcium triplet line is different for each line. Nonetheless, I find that my measures of the cores of the triplets do not show very much scatter. Consequently, I am a bit uncertain of that effect, as you described it.

(3) Concerning the infrared data of Gehrz, Hackwell, and Jones, I believe that their comment concerning $\zeta$ Tau and the objections to an infrared companion there would also apply to $\phi$ Per. The stars are too close; there is only about $1\frac{1}{2}$ AU between the two.

*Cowley:* The quoted rotational velocities for $\phi$ Per are widely discrepant. If you have two components that are both B-type stars, depending upon the phase of the observations and did not realize that there were separate lines, you would infer a broader profile and therefore a higher rotational velocity. It would be very interesting on very low noise spectrum scans to get the rotational velocities of both of the components, which would probably be lower than any of the quoted values.

*Peters:* We also have a series of spectrograms (5.5 Å mm$^{-1}$) of $\phi$ Per on IIIa-J plates and we see no evidence of duplicity. $\phi$ Per has strong Fe II emission and significant He I emission, which is also variable. I am wondering if what you are measuring is the variable helium emission and not the line shifts. The equivalent width of $\lambda$ 4026 is about 0.8 Å, which is 30% lower than one observes in non-Be stars of similar spectral type. In other words, everything is consistent with significant emission filling.

*Hendry:* One of the reasons I cannot be measuring the emission effects in the line is because the secondary component is the stronger component. What you should be objecting to is how do I measure the primary component, because it is broader and less intense.

*Meisel:* Berg and I have recently studied (*Astrophys. J.*, June 1975) the $\lambda$ 10 830 structure in Spica with 1.2 Å resolution, where the components are of spectral type B1 and B2$^+$. It is relatively easy to see lines of both components, and measure radial velocities as well as rotational velocities. Hence high resolution observations of $\lambda$ 10 830 in $\phi$ Per may help to resolve the question of the helium lines and the nature of the components.

*Massa:* The equivalent width of the helium lines is small, even for a star of early spectral type. We have scanner observations of $\phi$ Per, and the Balmer jump appears to be in emission, so you probably have continuum which is veiling the lines.

*Peters:* We have obtained several scans of $\phi$ Per, none of which show a negative (emission) Balmer discontinuity. We used the Hayes-Latham system of absolute calibration to reduce the scans. We do see some emission due to the envelope shortward of the Balmer discontinuity, however. We fit the energy distribution of $\phi$ Per to a 28 000 K, log $g$ = 4 Princeton model atmosphere.