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Investigation of the Shell Stars o And and ø Per, and of the Eclipsing Binary β Lyr

Final Technical Report
for the period May 1, 1974 through December 31, 1975

Principal Investigator: Miroslav Plavec

Department of Astronomy
University of California
Los Angeles, CA 90024

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I. Introduction

This Final Report summarizes the status of the work on the project at the time of the expiration of the grant, i.e. December 31, 1975. The grant covered the period May 1, 1974 through December 31, 1975 (including the extension period without additional funds, May 1, 1975 through December 31, 1975).

The original idea of the project was based on the assumption that in all three stars to be investigated, there is a reasonable chance to detect lines of the secondary component in the far UV. The chance was particularly strong in β Lyrae where recent work has shown rather convincingly that the invisible component is the more massive star in the system; therefore it was reasonable to look for a hot compact object with detectable lines in the far UV. ø Persei is almost certainly a binary star, as shown most convincingly by Hynek, who suggested that both components are B stars. Hynek's model has recently been developed by Hendry (1975), who made a case for a B3V secondary. This, too, gave reasonable hopes for detecting the secondary lines in the Copernicus spectra. The duplicity of o Andromedae remains highly cohtroversial. One can argue for it from the general hypothesis tnat many Be stars and shell stars are generated by mass transfer in binary systems (Plavec, 1975 and references therein; Kříž and Harmanec, 1975; Polidan and Peters, 1975; Plavec, Polidan, and Peters, 1973). Or one can accept the rather controversial photometric observations by Schmidt (1959) who suggested that the star is an eclipsing binary, with components approximately B6.5 V and B 7.5 V, but the combined spectrum is often veiled by a common outer envelope, in which the shell lines arise.

The hope to detect and identify the secondary components dictated the strategy even in the proposed budget. A considerable part of the grant was to be used on computer, running the evolutionary codes for binary star evolution, as well as programs computing the mass streams between the components.

However, no secondary lines were detected in any of the three components. Instead, all three stars showed rather complicated spectra, which require a very detailed spectroscopic analysis. The far UV spectrum of β Lyrae is clearly peculiar, with a multitude of emission lines not observed in any other star so far scanned with Copernicus. This made this star at once the most interesting and also, in a sense, easier to study. The other two stars display a spectrum rich in absorption lines, some of them being fairly broad (as expected for photospheric lines of rapidly rotating objects), some sharp. The latter, clearly non-photospheric lines, posed a special problem, since at the beginning of the project it was not clear which line is interstellar and which is circumstellar. In other words, the degree of peculiarity of the spectra of ø Persei and o Andromedae could not be established until surveys of normal stars and of interstellar lines were available.

The work on β Lyrae will be reviewed rather briefly in this Final Report. Two papers have already been published in which the working team presents the results of observations with Copernicus, their discussion and interpretation. These papers are listed at the end of this Report. I believe that the work on β Lyrae has been among the best results so far obtained with Copernicus, and that it has also contributed significantly to the current broad discussion on the presence of black holes in binary systems.

My work on β Lyrae was terminated in November, 1974, and since then I have concentrated on ϕ Persei and o Andromedae. Already the work on β Lyrae signaled that the initially planned approach, envisaging a rather heavy use of sophisticated computer codes, must be revised. The first steps in the evaluation of the raw observational data: measurement of the spectral lines, isolation of weak lines from noise, identification of lines in available (but incomplete) multiplet tables, measurements of equivalent widths, radial velocities, restoration of selected line profiles, etc., requires much less extensive computer usage and much more of detailed and careful "manual" work. As a consequence, in order to make further progress on the project, considerable savings had to be made in the budget on computer funds and other items (travel, publication costs), and more money was needed for the assistance of a graduate student. The phase of basic reduction of the acquired data is now essentially concluded. The reports on ϕ Persei (section III of the present report) and on o Andromedae (section IV) are preliminary, since it will take me several more months to complete publishable articles.

Until now, we have generated extensive lists of (1) lines of probably present elements and ions with laboratory wavelengths, taken from the multiplet lists by Moore and by Kelly and Palumbo (632 lines); (2) interstellar atomic and molecular lines from the list by Morton (1975) and the Princeton list of molecular hydrogen lines (a total of 533 lines); (3) lines observed and identified in the spectrum of η C Ma by Underhill (1974) (460 lines); (4) lines found in the course of this project in the UV spectrum scans of ϕ Per, o And, α Gru, λ Sco and 3-4 other comparison spectra (896 lines listed until now; the work has not yet been completed). Based on the intercomparison of these lists, a complete list of line identifications is being prepared (and is well advanced) separately for the hot star ϕ Persei (spectral type about B0.5 IV) and for the cooler o Andromedae (about B6 V).

A considerable effort was made to find and identify circumstellar lines in the spectra of both stars. Such identifications could not be considered reliable before the availability of Morton's list of interstellar lines; in certain cases, ambiguity remains even now. A very decisive step forward was the re-observation of o And in August 1975. It revealed substantial changes in many of the sharp and moderately sharp lines, thereby identifying them as circumstellar. For ϕ Persei, two runs were made already in 1973, but because of some misunderstandings, separate corrected sets of data were not available to me until February 1976. Duplicate observations of ø Per at two different orbital phases are less helpful for segregating circumstellar and interstellar lines, however, since the circumstellar shell lines in this star seem to vary very little with phase.

Also, an important part of the auxiliary work on data reduction has been the measurement of equivalent widths of a large number of lines. The research assistant has also worked under my guidance on comprehensive computer codes which enable us to calculate absorption and emission line profiles produced by extended atmospheres, using the principles developed by Marlborough and by Sobolev. This part of the work is also being prepared for publication in the near future. The underlying geometrical models of extended atmospheres differ from the type of envelopes considered by either Marlborough or Sobolev, and are the direct outcomes of my theoretical work on mass transfer in binary stars (see, for example, Plavec, 1973, or Plavec, Ulrich and Polidan, 1974). When the basic reduction of the data on ø Per and o And is finished, an attempt will be made to study these stars in the light of the above-mentioned theoretical models of circumstellar disks generated by mass transfer. Thus, in this respect the work reported here is related to my studies of mass transfer and duplicity of Be stars and shell stars, as presented also at the I.A.U. Symposium No. 71 on Be Stars and Shell Stars at Bass River, in September 1975 (to be published by Reidel, edited by A. Slettebak).

The two Preliminary Reports that follow have been made available to, and used by, T. P. Snow in his review paper "A Review of Ultraviolet Astronomical Research with the Copernicus satellite," 1976 (submitted to Earth and Extraterrestrial Sciences).

II. Final Report on β Lyrae

In order to study β Lyrae, I organized an ad hoc working group of several outstanding investigators interested in the project: Dr. M. Hack of Trieste, Dr. J. B. Hutchings of Victoria, Dr. Y. Kondo of Houston, Dr. G. E. McCluskey of Bethlehem, Pa. The participation of my research assistant, R. S. Polidan, was so important that he co-authored the papers resulting from this cooperation. My foremost task was to make a complete identification of all the emission lines in the spectrum, and then to participate in the formulation of a model explaining the observations. We identified over 200 lines, which fall essentially in two categories: emission lines, some associated with shortward-displaced absorptions (thus forming the P Cygni-type profiles), and interstellar absorption lines. The few stellar absorption lines observed longwards of 2200 A are due to the visible B8 component.

The spectrum of β Lyrae was scanned at four orbital phases: at the two eclipses, and at quadratures. The emission lines show little variation in radial velocity, intensity or shape with phase. Thus we have observed an extended envelope surrounding the whole binary system. The P Cygni profiles indicate an outflow of material, but their shape suggests that the predominant motions in this envelope are rotational. The most interesting discovery is the presence (in emission) of the N V doublet at λ 1239 and 1243 A. This ion requires a high degree of ionization and has not been observed in any other Copernicus star cooler than B0; in fact, its strength in β Lyrae surpasses even that in the hottest observed stars of spectral types about O5. We attempted to explain the presence of such a hot plasma around β Lyrae. It can be argued rather convincingly that the source of excitation of the emission lines is non-radiative and most likely collisional. The N V lines are probably formed rather close to a disk which is supposed to surround the invisible secondary component.

The nature of this disk and of the secondary component remains controversial. One possibility is that the secondary is a black hole surrounded by an accretion disk. If so, we have shown that the accretion regime is highly supercritical, by a factor of about 10^3. The qualitative consequences of this hypothesis appear to be satisfied by our observations; however, my effort to apply a Shakura-Sunyaev type model to β Lyrae led to very serious inconsistencies. It is impossible to decide if this really means that the black-hole model is not applicable: I strongly suspect that the Shakura-Sunyaev model suffers from serious internal inconsistencies. The other possible hypothesis, namely that β Lyrae is a younger system observed at the first phase of mass transfer of type B appears simpler and more attractive at this time. However, it is not easy to reconcile this model with our observations of very hot plasma being present in the equatorial plane, or with the observed helium overabundance of the visible B 8 star. In any case, this model requires further calculations of non-conservative mass transfer in binary systems; I am working on these models now, but they are outside the scope of the present project, already because of its severe budgetary restrictions.

III. A Preliminary Report on the Far UV Spectrum of Phi Persei, (as presented at the San Diego meeting of the A.A.S., August 1975).

The star ø Persei is a well- wn spectrum variable with a period of 126.696 days. The recu..ent changes in its spectrum were interpreted in terms of a binary nature of the star mainly by Hynek (1940, 1944, 1955). Hynek's concept of the star has recently been developed by Mrs. Hendry (Indiana meeting of the AAS, 1975). She suggests that the system consists of a very rapidly rotating B0 V star, surrounded by a large gaseous ring, and a more normal B3 V star.

The far ultraviolet spectrum of ø Persei was scanned with the Copernicus spectrometer in September 1973 at two different epochs, corresponding to phases 0.74 P = 94 days, and 0.96 P = 121 days, respectively. In keeping with the earlier work, phase 0.0 corresponds to conjunction with the B0 star in front. Terrestrial spectra were obtained almost simultaneously with the first set of Copernicus scans at the Lick Observatory: thanks to the assistance of several UCLA graduate students, I have high-dispersion spectra in the blue region, image-tube spectra in the red and infrared, and spectral scans covering a very broad spectral region. Thus for phase 0.74 P we have what may well be the most complete record of any spectrum simultaneously observed, namely an uninterrupted scan from λλ 1000 through 8600 A. The coverage of the latter phase is not much worse thanks to a spectrum taken only a few days later by Dr. Heard of the David Dunlap Observatory; also, if the spectral features do really occur periodically, my own spectrum taken at Victoria in 1972 corresponds to the same phase.

The appearance of the spectrum in the ordinary photographic region is quite different at the two phases, as Figure 1 shows. At phase 0.96, there appear very strong, narrow, and deep absorption cores in the Balmer lines from H_γ through at least H_{25} very clearly, and weaker cores can be traced as far as H_{31}. The radial velocity of all the cores is about -0.7 km/s. The radial velocity predicted for this phase by Hendry from her study of the helium lines and lines of other elements is -12 km/s.

At phase 0.74, the sharp hydrogen cores are practically absent. The remaining features in the few lower Balmer lines shows signs of duplicity. Otherwise, however, there remain symptoms of an extensive emitting envelope mainly in the form of emission lines. In fact, the emission lines are not markedly different at the two phases. If anything, they may be slightly stronger when the strong cores are absent. Hα is in both cases an extremely strong emission with little trace of an absorption component. Double emission components are seen up to about H_{10}, although they are quite weak beyond H_δ. Although the total strength is not markedly different at the two phases, there is a significant V/R variation: V lobes are stronger at phase 0.96 while R lobes are stronger at phase 0.74. O I 7774 shows an emission and a shell absorption component. Many Fe II lines show double emission, for example λλ 7712, 4629, 4550, 4233. Some of the helium lines display a weak emission component, too, in particular λλ 6678 and 7065.

The two different phases were specially selected for the Copernicus observations in the hope of detecting significant differences in the ultraviolet spectra. One could anticipate three possible types of changes:

(1) A displacement in the radial velocities of the lines of the primary (B0) component by about 32 km/s, corresponding to a wavelength shift of about 0.13 A at λ~ 1200 A.

(2) Possible doubling of some lines at elongation (0.74 P), with a velocity difference of 120 km/s, corresponding to a wavelength difference of 0.5 A λ~ 1200 A.

(3) Some marked differences in the presence, appearance or intensity of the shell lines, in keeping with the marked variation seen in the hydrogen lines.

No such changes of any of the three kinds have been found. The absence of line splitting is the least surprising. A B3 V star must be significantly fainter than a B0 V star. This is, however, true for the ordinary photographic region as well, where the difference in the B magnitude should amount to almost 3 magnitudes. Nevertheless, Mrs. Hendry claims to have seen and measured the helium lines of the secondary and considers them as in fact better visible than those of the primary. Two factors may help to improve the unfavorable light ratio: the helium lines are known to be strongest at B3, and if that star rotates more slowly, its lines will be better defined. Nevertheless, I do not think that these two factors can reverse the relative strength of the lines, so Hendry's measurements leave a possibility of an abnormally bright B3 star, which then might show up in the ultraviolet. It has not been found, however.

The difference in radial velocities predicted for the primary component, 0.13 A, is too small to be reliably detected in the low dispersion mode where the nominal resolution is 0.20 A. A number of lines were scanned in the high-dispersion (U1) mode with nominal resolution of 0.02 A. No significant systematic differences in radial velocities were detected. Again, this statement must be qualified. The lines scanned were selected primarily for the purpose of studying interstellar material, and indeed the essential invariability with phase, and similarity of depths and profiles with the lines studied by Morton in ζ Oph strongly suggest that these lines are formed very far from the star, and from the whole system. Among the lines in this category are λλ 1336 of C II 1, 1302 of O I 2, 1265 of Si II 4, 1251 S II 1, 1134 N I 2, and many others.

The failure to detect line splitting or radial velocity shifts means that our observations furnish no evidence that the star is indeed a binary. From my preceding remarks it is clear, however, that it can hardly be taken as a serious evidence against the binary hypothesis.

The next question is whether the object has an anomalous ultraviolet spectrum, and whether its spectrum changes with phase or not.

There are no emission lines observed at these two phases in the region between λλ 1000 and 2900. This is rather surprising in view of the strong emission observed mainly in the red spectral region. This also implies that ϕ Persei must be different in nature from β Lyrae, if such a proof was indeed necessary.

The very rapid rotation of the (primary) star makes all photospheric lines extremely broad and shallow, so that the far UV spectrum is quite smooth and flat at places where other stars of a similar spectral type (e.g. β Cen, B1 III or ε Per, B0.5 III) display distinct photospheric lines. Very few features in the spectrum of ϕ Persei can be considered to be pure photospheric lines. One may be λ 1206 of Si III 2. The resonance lines of Si IV at λλ 1394 and 1403 may be mostly photospheric and their asymmetry may suggest a stellar-wind component, but the signal at these wavelengths is too weak to permit any definite statement based on the examination of the spectrum of ϕ Persei alone.

The distribution of energy in the continuous spectrum is very similar to that of β Centauri, B1 III, or of ε Persei, B0.5 III. At first sight, ϕ Persei appears to be closer to B1, but a proper correction for interstellar reddening shifts it closer to B0.5.

However, reddening in itself presents a serious problem in ϕ Persei. Good colors exist for the star: $U-B = -0^{m}.93$, $B-V = -0^{m}.04$, but they place the star in an unusual position in the color-color diagram -- a normal U-B but a strongly reddened B-V, giving $E(B-V)=0^{m}.22$. Thus either the U magnitude is contaminated by Balmer emission or the star's reddening is mostly intrinsic. Most likely both effects are operating, because the energy distribution found by Keyes and Wright (UCLA graduate students cooperating on this project) with the Crossley scanner at Lick indicates both some Balmer emission as well as excess radiation beginning at about λ 6000 and growing to the red.

Thus there is ample evidence for a circumstellar shell being present around ϕ Persei at all times. The problem is how to separate the shell lines from circumstellar lines. Since the low-dispersion spectra do not permit separation by means of radial velocity differences as these are apparently quite small, it is necessary to look for sharp lines which are either absent or considerably weaker in the comparison spectra than in ϕ Persei. 99 such lines were found in the spectral region λλ 1010 through 1405. In what follows, an attempt is made at a preliminary identification of these shell lines.

Carbon undoubtedly contributes to the shell spectrum, in particular C II, multiplets 1, 2, and 12; however, most likely also C I is present (multiplets 4, 5, 7, 11, 14, 17, 29, 30, and 50), and possibly also C III 9.

Nitrogen is definitely present as N I with zero-volt multiplets 1 and 2, but these lines may well be purely interstellar. The only other ion of nitrogen clearly present in the shell spectrum is N II multiplet 1.

O VI 1 at 1031.9 is sharp and moderately strong.

Si II significantly contributes to the shell spectrum by its zero-volt lines, multiplets 3, 4, and 5; transitions from the 5.3 eV level have not been found with certainty. The Si III 2 line at λ 1206.5 is probably mostly photospheric. Si III multiplets 4 and 5 give good strong shell lines, evidence on higher multiplets is doubtful. The lower level of the multiplets 4 and 5 is 6.6 eV, thus here we have shell lines from a non-zerovolt level.

Si IV has not been established unambiguously.

Phosphorus is probably represented only by the P III 1 lines.

As for sulfur, S II 1 zero-volt lines are clearly present; no clear evidence of higher multiplets. S III is definitely represented by multiplets 1 and 2; judging by the 1201.7 line, it gives quite strong shell lines. However, most of them are so badly blended that the contribution of S III is difficult to evaluate. S IV 1 gives strong lines, although again their strength may be partly due to blending.

Argon is represented by multiplets A I 1 and 2; the lines are not quite sharp, but the shell contribution to the interstellar line, if any, is difficult to establish.

Only one multiplet of titanium was found with certainty, namely Ti III 2. This element, which furnishes so many lines in typical shell spectra in the ordinary photographic region, is thus only weakly represented.

Cr III has very many listed lines in the region under investigation, and accidental coincidences are inevitable. There are individual shell lines for which Cr III is the best identification, but none of the 15 multiplets studied gives uniformly good representation with line intensity ratios in agreement with prediction. A tentative conclusion is that Cr III is probably observed but does not show strongly.

Rather similar problems are with V III (multiplets 1, 2, 3) and Mn II, where multiplets 15, 24, 25, 27, 28, 40, 42, and 43 may be present. Some lines of Mn III are also possibly present.

It appears that the most prominent contributor to the shell of ø Persei is Fe III. Multiplet 1 is seen in full and easily identified. In addition, lines of multiplets 20, 26, 27, 28, 40 and 41 probably appear as weaker features; the lower level for the two last multiplet is at 3.8 eV. Frequent blends with lines of Fe II make identifications difficult. Fe II is no doubt present also 18, 19, 51, and 155. Nevertheless, contrary to the case of the cooler star o And, in ø Persei Fe III appears to dominate over Fe II.

Some shell lines are difficult to explain without invoking Cu II (multiplets 23, 24, 26, 56, and 58), and Co III 8.

One concludes that the far ultraviolet spectrum of ø Persei is quite rich in shell lines. However, at the two epochs at which the observations were made, the spectrometer recorded only minor differences in the intensity and appearance of the shell lines, as if the shell surrounded the whole system as a large cloud which may not be significantly perturbed by the motion of the two binary components, and by streaming between them. This conclusion is naturally based on two observations only. The conspicous variability of the hydrogen lines compared with the small variations of the far UV shell lines represent an important constraint on future models of this star. Additional observations with Copernicus are certainly desirable and I plan to propose them for the fall of 1976.

IV. A Preliminary Report on the Far UV Spectrum of Omicron Andromedae

The photospheric spectrum of Omicron Andromedae in the region λλ 1000 - 1400 A is very similar to that of Alpha Gruis, B7 IV. In the blue, too, both stars have very similar spectral classes, and luminosity classes as well, since o And was recently classified by Peters (1975) as of luminosity class III. α Gruis is closer to us (d = 30 pc), while o And, if their luminosities are indeed equal, must be about twice as far. Also, o And is much closer to the galactic plane (β = -16°) than is α Gru (β = -52°).

Nevertheless, it is doubtful if the combined effect of distance and galactic latitude can explain the fact that the interstellar lines are almost absent from the spectrum of α Gru while they are quite strong in o And. This is in particular true about the lines of molecular hydrogen. Also, the continuum of o And shows a color excess of E(B-V)=+0.05. I suspect that part of the reddening and part of the strength of the "interstellar" line strength is due to a circumstellar envelope. This suspicion is corroborated by the presence of additional sharp lines which are not in Morton's list of interstellar lines in the spectrum of ζ Ophiuchi. These additional sharp lines are mostly Fe II, multiplet 10, and also probably C I, multiplets 23 and 30. The spectral interval under close scrutiny was in this case only the region λλ 1040 to 1205, where the signal is sufficiently strong to make noise unimportant.

So far, the description has referred to the spectrum of o And as observed in 1973. It was reobserved again in August 1975. The reason for reobservation was the appearance of weak shell absorption cores detected in July 1975. Omicron Andromedae is a recurrent shell star. In the years 1946 through 1951, it displayed a well-developed metallic shell spectrum with narrow sharp Balmer cores, and sharp lines of Fe II, Ni II, and (much weaker) Ti II, Sr II, Sc II, Ca I, Fe I. (Slettebak, 1952). In 1952, the metallic shell lines disappeared, and eventually in 1963-64 the spectrum was purely photospheric with no shell components. Pasinetti (MSAI 39, 73, 1968) claims that the strong shell reappears periodically in a period of about 30 years, and that the shell development phase takes about 12 years. If so, we should anticipate a new metallic shell in 1976/77. This is why the reappearance of the Balmer cores in July 1975 attracted attention, since it may signal the onset of a new shell.

However, one must be very cautious. The case for the 30-years periodicity is rather weak, for the previous alleged strong shell stages, in about 1890 and 1921, were observed quite inadequately. Even if the prediction of a new metallic shell phase in 1976/77 is correct, this does not necessarily imply that the cores observed in July 1975 do actually signal the buildup of the strong shell. For example, even stronger Balmer cores were observed in September 1974 (Pasinetti, IBVS 1044, 1975), and then weakened again.

There appears to be small-scale variability of the shell features in o And, and so far we have no reliable indicator which would signal and measure that (and if) the shell builds up gradually.

It is therefore very important to note that the 1975 Copernicus spectrum of o And shows many more shell features than did the 1973 spectrum. The conclusions that follow have been derived by qualitative inspection only, and such a qualitative comparison is not easy. Between 1973 and 1975, the sensitivity of the Copernicus spectrometer must have diminished by about a factor of five, so that noise causes much more serious problems with the 1975 spectrum. Only the spectral region λλ 1040 - 1205 was observed sufficiently well in both cases to warrant reliable comparison. Shortwards of λ 1040 the signal was weak in both cases; the same is true longwards of about λ 1350. However, also in the region λλ 1220 - 1350 the noise makes some of the sharp lines identified on the 1975 scans suspect of being spurious.

A preliminary examination of the best region, λλ 1040 through 1205, revealed 26 shell lines which are considerably stronger and deeper on the 1975 tracing, and 50 additional lines which have also probably strengthened. The typical picture is that a line which was rather broad and rounded in the 1973 spectrum appears to have developed one or more sharp components in the 1975 spectrum. The same trend is observed in the noisier region λλ 1220 through 1350. If one counts the more reliable lines only, then 12 are definitely and 22 probably enhanced in the 1975 spectrum.

A preliminary identification of the variable shell lines gives the following picture:

Some of the C I lines appear to be formed in the shell, and those due to multiplets 21, 22, 23, and 29 appear enhanced.

C II, multiplets 1 and 11 are also present as shell lines, but there is no definite evidence of strengthening.

The strong C III 4 blend at λ 1175 was a smooth, deep and broad line in 1973, but in 1975 it apparently developed individual narrow shell features in at least some of its components. This description, however, does not fully explain the distorted appearance of this blend in the 1975 spectrum; at places there seem to be less absorption in the shortward wing of the feature than it was in 1973.

Neutral nitrogen, multiplets N I 1, 2, and 7, give strong sharp lines which do not change and are probably interstellar; the same is true about N II 1.

Oxygen O I 2 at 1302.17 is sharp and probably interstellar.

Silicon in the singly ionized form gives a number of shell lines of different intensities, and some among them (multiplets 4 and 7) probably somewhat strengthened between 1973 and 1975.

Evidence on Si III and Si IV is not conclusive because of serious blending.

The lines of P II 2, when not blended, appear to be present as weak shell lines only, and without any conspicuous change. On the contrary, all three lines of P III 1 are enhanced in the 1975 spectrum. P IV is possibly present.

Sulfur: multiplets S II 1, 3, and 8 are most likely present in the shell and show strengthening; also S III 1 gives strong sharp lines which are much deeper in 1975 than in 1973.

The two strongest lines of argon, A I 1 and 2, are also probably deeper in the 1975 spectrum.

Lines of Ti III, multiplets 1 and 2, show up as shell lines on both scans, but are stronger in the 1975 spectrum.

Vanadium in the form V III has been suspected but not definitely found in the shell; some lines of multiplets 2 and 3 may be responsible for very weak shell lines, but there is no evidence of multiplet 1.

Similarly, the evidence for Mn II and Mn III is inconclusive.

The case of chromium is very ambiguous. As Cr II, this ion typically gives rise to many shell lines in the blue spectral region. Cr II has no lines in the region shortward of λ 1350. On the contrary, Cr III has so many listed lines there that accident coincidences with observed shell lines are inevitable. Since the number of such coincidences is rather small, there exists no compelling evidence in favor of Cr III.

Once ionized iron is known to supply many strong shell lines in typical metallic shells when observed in the blue spectral region. Shell lines due to Fe II 10 are most prominent among the shell lines seen already in the 1973 spectrum of o And. There is a fairly positive evidence of additional multiplets giving rise to new shell lines in the 1975 spectrum; these multiplets are in particular 9, 12, 15, 17, 18, 19, 48, and even 155 (lower level is still only 2.6 eV). There remains only one source of uncertainty, and this is possible contribution by the lines of Fe III. A good number of the Fe II lines are enhanced in the 1975 spectrum.

Multiplet 1 of Fe III is most likely present in full and contributes to the general strengthening of the 1975 shell. Relative contribution of Fe II and Fe III is difficult to establish; statistically, the evidence is in favor of Fe II. The next multiplets of Fe III in the region are 26 and 27, and they may again be present, although -- except for the line 1066.18 -- always in blends with other elements.

The general picture emerging after the first qualitative examination is not very clear. Slettebak (1952) concluded that a typical feature of the metallic shell spectrum of o And in 1951 was the predominance of Fe II over all other metals (Ti II, Sr II, Sc II, Ca I, Fe I). In August 1975, Fe II shell lines were the only ones to show up (very weakly) in the usually observed photographic part of the spectrum. It is therefore not surprising that Fe II is dominant in the $\lambda\lambda$ 1040 - 1350 domain, and that some of its lines were already present in 1973. Ti II, Cr II, and V II have no lines in the UV region studied, and the degree of ionization is probably not high enough for Cr III, V III, or Mn III to show up conspicuously. Some lines of Ti III are present, however, as are Fe III.

The remainder of the shell lines observed in the UV are due to light elements, and here we observe C I, C II, C III, Si II, P III, S II, and S III. The trend towards enhancement between 1973 and 1975 seems to be shown mainly by the lines corresponding to higher potentials of ionization and excitation. Since also the lines of molecular hydrogen indicate some degree of enhancement, this seems to corroborate my conclusion that a number of the sharp lines in the 1973 spectrum are circumstellar rather than interstellar. Thus the extended envelope around o And seems to show up better in the far UV than in the blue, and further observations promise to yield more sensitive indicators of shell buildup.

Since in the course of the work on the project, I have been regularly obtaining spectra of o And at the Lick Observatory (partly thanks to the cooperation of Dr. G. J. Peters and my research assistant Mr. R. S. Polidan), it will be possible to compare the changes in two different spectral regions.

The difference in behavior between ø Persei and o Andromedae is very interesting: a conspicuous variation in the photographic spectrum of ø Persei was accompanied by very modest changes in the far UV. In o Andromedae, exactly the opposite is true.

Both stars deserve further observations and it is my plan to propose new Copernicus observations in 1976. Independently of this, however, I plan to complete the project and publish a full account of the work as soon as my administrative duties permit.

Bibliography

a) Papers published under the present grant:

1. M. Hack, J. B. Hutchings, Y. Kondo, G. E. McCluskey, M. Plavec, and R. S. Polidan: 1974, Nature, 249, 534-536.

2. M. Hack, J. B. Hutchings, Y. Kondo, G. E. McCluskey, M. Plavec, and R. S. Polidan: 1975, Astrophys. J., 198, 453-465.

3. M. Plavec: The Far UV Spectrum of Phi Persei, 1975, Bull. Amer. Astron. Soc., 7, 405. (Presented at the 146th meeting of the Amer. Astron. Society, San Diego, August 1975).

   (Five copies of each publication are attached. The full text of the lecture at San Diego is included in the Final Report as Section IV).

b) Other papers by the author, partly related to the present grant:

1. M. Plavec, R. S. Polidan, and G. J. Peters: Relation between Shell Stars and Interacting Binaries: 1973, Bull. Amer. Astron. Soc., 5, 398-399. (Paper presented at the 141st meeting of the Amer. Astron. Society in Tucson, December 1973).

2. M. Plavec: Introductory Address, delivered at the I.A.U. Symposium No. 71 on Be Stars and Shell Stars, Bass River, September 1975. To be published by D. Reidel, ed. A. Slettebak, 1976.

3. M. Plavec: Final Remarks on the Binary Hypothesis for the Be Stars. Presented at the I.A.U. Symposium No. 71, see above.

4. M. Plavec: On the Algols, Red Spectra, Be Stars, and even Neutrinos. Invited paper presented at the I.A.U. Symposium No. 73 on Structure and Evolution of Close Binary Stars, Cambridge 1975.

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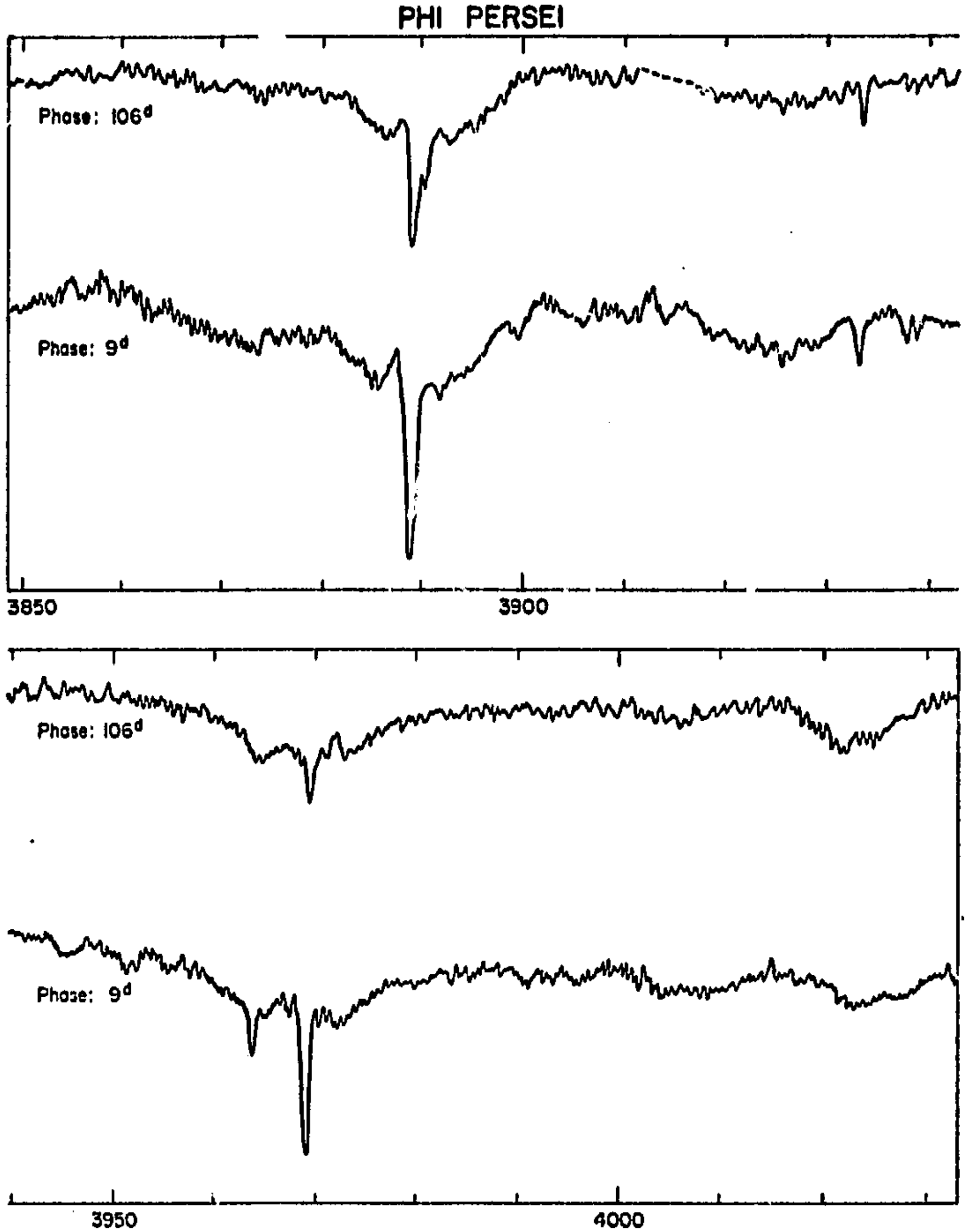
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Figure 1

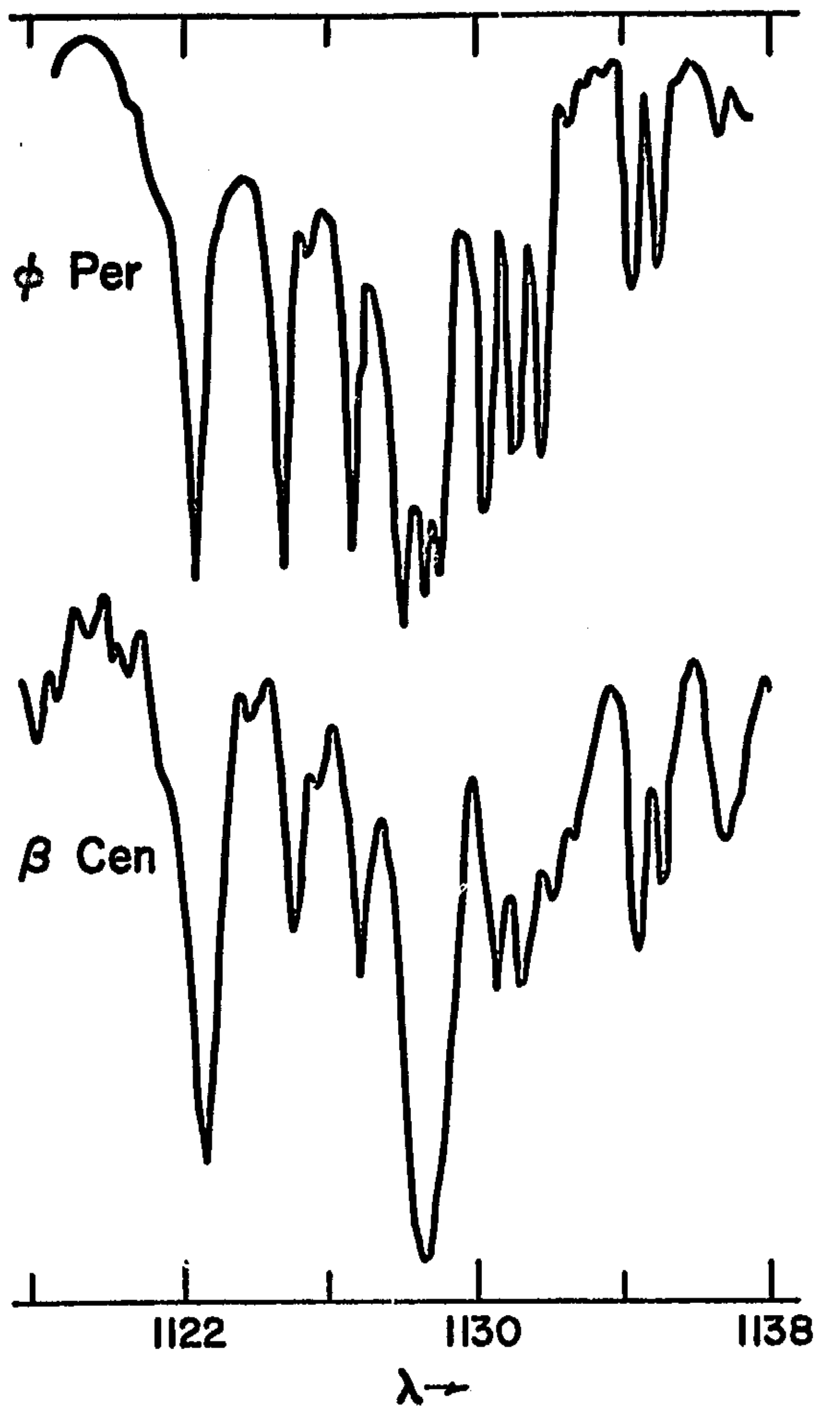

Figure 2