V HYDROGEN DEFICIENT BINARIES

HYDROGEN-POOR BINARY STARS

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ABSTRACT. Hydrogen-poor and helium-rich stars are easy to produce in interacting binaries. Thus they should be found among Population I binaries, in which a large-scale mass transfer has occurred between the components (possibly associated with mass loss from the system). For in such cases, those layers are now on the surface of the "loser" (and, most likely, also on the surface of the "gainer") that were subject to hydrogen burning and the associated mixing of processed material. Helium overabundance in these objects will be accompanied by an overabundance of nitrogen and underabundance of carbon, as a result of the CNO process. All the Algol-like semidetached binaries should be mild helium stars; so far this has been demonstrated only in β Lyrae, for the He/H ratio is not extreme in such cases. Extreme helium stars require a more complex process, with two stages of mass transfer and/or loss ("case BB"); υ Sagittarii and KS Persei seem to be good examples of this process. The optically invisible components of these two stars seem to have been detected with the IUE. Good model atmospheres do not exist yet, so caution must be exercised in interpreting the UV data.

1. ALGOL BINARIES AS MILDLY HYDROGEN-POOR STARS

Close binary star systems represent the simplest way to produce hydrogen-deficient and helium-rich stars. In every eclipsing binary system of the Algol type, both stars should show deficiency of hydrogen. Algol binaries are semi-detached systems: the mass-losing star ("loser") fills its critical Roche lobe and gas streams through the Lagrangian L_1 point toward the "gainer." The mass-transferring process begins when the more massive component fills all its available volume during its secular expansion. In many systems which we observe, this happened after the more massive star had left the main sequence and was crossing the Hertzsprung gap in the H-R diagram, expanding to become a red giant; this mode of mass transfer is known as "case B."

Soon after the onset of mass transfer, the process accelerates rapidly and the rate at which the loser loses mass may be quite high (on order of 10^{-4} $m_\odot$ per year for stars initially near 10 $m_\odot$. After the

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loser becomes the less massive component, the process slows down significantly, and it is at this "slow phase" that we observe the *Algol binaries*. Algol, or β Persei, is the brightest object of this type, but we know many others, since the eclipses of the hotter but smaller gainer by the cooler but larger loser easily attract attention.

The initially more massive star filled its critical Roche lobe at a time when all hydrogen had already been exhausted in the core, and energy is now generated by hydrogen burning in a shell surrounding the inert, helium-rich core. This shell acts as a barrier for mass loss, which stops when just a bit of the star's envelope is left outside this hydrogen-burning shell. Interior to that shell, the evolution of the core proceeds undisturbed, as if nothing were happening to the star. That is, the helium-rich core shrinks, becoming hotter and denser. In stars initially less massive than 2.7 $m_\odot$, the contraction and heating of the core is halted by electron degeneracy. When the core stops contracting, there is also no longer any push on the envelope outside the shell; rather, whatever has been left of it loses the support from within and collapses on the shell. The star detaches itself from its critical Roche lobe and the mass outflow ceases. The reduction in radius is so drastic that the star virtually becomes a ready-made white dwarf.

In stars initially more massive than 2.7 $m_\odot$ contraction is halted by the ignition of helium, which now begins to be converted into carbon by the triple-alpha process. This event reverses contraction in the core into expansion, and by the so-called "mirror effect" (Kippenhahn and Weigert 1967), the envelope begins to shrink. Again, the star detaches itself from the Roche lobe and mass loss ends.

At the time of the termination of the mass transfer, *the hydrogen content at the surface of the star is about $X = 0.20$ (by mass)* (Kriz 1969; De Greve, de Loore and van Dessel 1978), compared to the initial (adopted) value of $X = 0.70$. Why should hydrogen be deficient at the surface of the loser? The layers now exposed were initially part of the convective core of the star. Hydrogen burning did not actually occur there, but convective mixing maintained the same chemical composition throughout the region, as long as it remained convective. But the convective core shrinks with time, so that the hydrogen content in the now-exposed layers is eventually stabilized.

If the hydrogen content by mass is down to about $X = 0.20$, then the helium content is about $Y = 0.77$. Since the atomic masses are in the ratio 4:1, we can say that at the end of mass transfer in case B, we have a "half-and-half" mixture of hydrogen and helium, as far as the number of atoms is concerned. For a long time, the loser has been slowly sending this helium-enriched material toward the gainer. Therefore, we can expect that the atmosphere of the gainer, too, will be helium-enriched and, if there is any accretion disk around the gainer, or any other kind of circumstellar material, that material, too, should show hydrogen deficiency.

However, we cannot expect striking effects. After all, hydrogen with its high continuous and line opacity still remains plentiful. Klinglesmith (1971) published models with $X = 0.143$ and $Y = 0.857$, which give us good insight. A comparison of these models with the more detailed models calculated by Kurucz (1979) for atmospheres with normal composition shows that in the optical spectral region, deviations in the continuous flux are likely to be negligible. Larger deviations show in the far ultraviolet (in the region of the short-wavelength IUE "SWP" camera), but the picture is not clear for the following reason: Kurucz's models take into account line blanketing by thousands of lines, while Klinglesmith considered only line blanketing by hydrogen. The far ultraviolet region is rich on strong absorption lines even for temperatures 10,000 - 14,000°K considered by Klinglesmith, and the more transparent hydrogen-poor atmosphere produces deeper absorption lines than the normal atmosphere. This effect shows very strongly in Klinglesmith's models of the Balmer lines, which are strikingly deeper than in normal atmospheres. The same curious consequence of mild hydrogen deficiency also makes the Balmer jump deeper. These predictions cannot be tested on Algol systems, though. Many of them are surrounded by circumstellar matter which tends to fill in the Balmer absorptions to such a degree that we often observe emission lines instead. Similarly, a circumstellar hydrogen cloud often produces emission at the Balmer discontinuity, observed in the combined spectrum of the system as the so-called "(near)-ultraviolet excess."

It seems that the only way in which to detect the mild hydrogen deficiency in Algols is to study the metallic-line profiles at high dispersion and compare them with profiles calculated by means of spectrum synthesis on the basis of Klinglesmith's (or some more up-to-date) hydrogen-poor models. So far, this was succesfully done only in one case, by Balachandran *et al.* (1986) for the famous binary β Lyrae. There is another important abundance effect closely associated with depletion of hydrogen, namely a fairly drastic change of the abundance ratios C/N or even C/N/O as a by-product of the CNO bi-cycle. Most of carbon has been converted into nitrogen in the hydrogen-poor region, and this is precisely what the Texas people established for β Lyrae. They conclude that the Klinglesmith model with $X = 0.143$, $Y = 0.857$ (that is, by numbers of atoms, $N[H] = 0.4$, $N[He] = 0.6$)) is quite fitting. Considering the uncertainties involved at each step, the agreement with the prediction from the theory of mass transfer is very satisfactory. Surprisingly, it also tells us that β Lyrae is near the end of the mass-transfer episode rather than in its rapid phase. The currently adopted large inequality in masses, about 2 $m_\odot$ for the loser and 12 $m_\odot$ for the gainer, supports this conclusion.

Perhaps the fairly large strength of the circumstellar emission lines of He I in β Lyrae also indicates the overabundance of helium (see Figure 1). The circumstellar emission lines offer another method for exploring the abundance anomalies in Algols. I have discovered far-ultraviolet emission lines in at least five binaries apparently similar to β Lyrae (the W Serpentis stars) and in thirteen "ordinary" Algols (Plavec 1980; Plavec *et al.* 1984). Again, the best approach is to compare the relative strengths of the N V doublet at 1240 Å with the C IV doublet at 1550 Å. My spectra do show considerable differences between individual objects, and some show N V as stronger, contrary to what one expects for solar-like abundances.

2. BINARIES WITH EXTREME HELIUM STARS

While in β Lyrae and in the Algols the hydrogen deficiency is so mild that we must painstakingly look for it, two binary stars have long been known to show striking hydrogen deficiency in the spectra. These are υ Sagittarii (HD 181615/181616) and KS Persei (HD 30353). There seems to be no more than one hydrogen atom per 10,000 helium atoms in the atmospheres of the visible components in these systems. This practically complete depletion of hydrogen cannot be achieved in the mass transfer case B. Case C (in which the mass transfer starts when the more massive star is an expanding helium-buring giant) seems to be indicated by the long orbital periods (138 days for υ Sgr and 360 days for KS Persei). However, case C does not reduce X below 0.20 either (Lauterborn 1970), and does not therefore offer any good explanation.

I proposed a solution of this dilemma (Plavec 1973) in an invited talk which passed largely unnoticed. Paczynski (1971) studied the evolution of pure helium stars on the helium main sequence and concluded that they will move into the giant region of the H-R diagram provided their masses lie between about 1 and 2 m$_\odot$. At about the same time, Harmanec (1970) and Horn (1971) studied the final stages of case B for moderately massive stars. These stars shrink after the mass loss episode has ended and move close to the helium main sequence. Horn pointed out that mixing of the outermost layers can be expected after the hydrogen-burning shell dies out, since rapid contraction may cause rotational instability. This process will substantially reduce the abundance of hydrogen in the atmosphere, and whatever is left, will be passed over to the gainer since the loser may easily reach its critical Roche lobe for the second time. My suggestion was that υ Sagittarii and KS Persei are systems at this stage of evolution, which was subsequently called case BB by Delgado and Thomas (1981). The same model was independently rediscovered by Schönberner and Drilling (1983). Substantial progress in the theory of binary star evolution between 1973 and 1983 made it possible for them to make some more detailed comments. De Greve and de Loore (1977) found that case BB occurs for initial primaries in the range between about 8 and 15 m$_\odot$. Since the final mass after case B is given approximately as $m_{1f} = 0.04 \times m_{1i}^{1.62}$ (De Greve and de Loore 1977; for a more accurate formula, see De Greve 1982), these stars end up as helium stars with masses from just above the Chandrasekhar limit up to about 3.3 m$_\odot$. In the subsequent evolution, these helium stars expand again and cross the H-R diagram from left to right to become supergiants.

From various lines of evidence we know that υ Sagittarii and KS Persei are supergiants, and that their effective temperature cannot be far from 10,000°K (Schönberner and Drilling 1983, Drilling and Schönberner 1982). Helium stars with masses below 2 m$_\odot$ reach that region of the H-R diagram after they have exhausted helium in their cores and start burning helium in a shell. They expand to such large radii that they will fill the critical Roche lobe for the second time in most binary systems, and a new phase of mass transfer begins: this is the BB phase, at the end of which the helium-buring shell declines and the star shrinks again.

Our idea is that υ Sagittarii and KS Persei are observed just during the BB stage. This stage is short-lived, lasting on the order of 30,000 years, but the loser is a prominent supergiant, calling attention to itself by its anomnalous chemical composition. Thus, in principle, the two peculiar binaries seem to be well explained. However, there are several constraints on the model which enable us to check on it. I will discuss here υ Sagittarii, with which I am more familiar. The star KS Persei (HD 30353) was thoroughly studied by Danzinger, Wallerstein and Böhm-Vitense (1967) and its ultraviolet spectrum was studied by Drilling and Schönberner (1982). KS Persei and υ Sagittarii show so many similarities that my "caveats" formulated in the following section will also apply to KS Persei.

3. CHECKING THE MODEL OF UPSILON SAGITTARII

Upsilon Sagittarii shows some signs that the mass loss is still going on, for example its Hα line is seen in emission in spite of the extreme hydrogen deficiency which must prevail in the circumstellar envelope as well. But the system is not hopelessly obscured by circumstellar matter, so we can assume that the loser is in a slower phase of mass loss. We can then conjecture that the mass of the loser will not be far from 1.5 $m_\odot$. Optically, the loser is the only visible component of the binary system. Its radial velocity curve derived by Wilson (1914) and by Seydel (1929) appears to be well determined (Eggen, Kron and Greenstein 1950), and gives K(1) = 49.1 km s^{-1} with an indication of a small eccentricity ($e \simeq 0.05$). The orbital period of the system is 137.96 days. This leads to a mass function f(m) = 1.693. With our estimate of m(1) = 1.5 $m_\odot$ within fairly small limits, the mass determination still requires the knowledge of inclination i. There were reports of eclipses, which would constrain this quantity very significantly, to values not very far from 90°. Unfortunately, there is no certainty.

Gaposchkin (1945) announced the detection of two minima of depths 0.15 mag and 0.08 mag respectively, from a survey of the Harvard patrol photographic plates. Because of the very small ranges, one must accept this report with caution. Eggen, Kron and Greenstein (1950) did observe the two minima photoelectrically, but with only one-half the amplitudes. A systematic coverage of υ Sagittarii in 1979 by J.J. Dobias, R.P.S. Stone and me failed to detect these eclipses, although small light fluctuations were seen, and very shallow eclipses could be obliterated by them. The deeper minimum, according to the two above-mentioned sources, occurs when a hotter but unseen component is to be eclipsed. This component would then be much smaller and optically fainter, so the shallowness of the eclipses does not surprise. Perhaps $i = 80°$ is a good guess if the eclipses really exist; but if not, i may be much smaller. We must consider both alternatives.

If the system is eclipsing, then the mass of the gainer should be about 3.6 $m_\odot$ and the mass ratio would be 2.4:1 in its favor. The separation between the components would be about 190 $R_\odot$ and the mean radius of the loser would be near 60 $R_\odot$. We could then predict a radial velocity range of K(g) = 20 km s^{-1} for the unseen star. If the system does not eclipse and i = 60°, the mass of the gainer would be 4.6 $m_\odot$, and for i = 40° it would be 8.8 $m_\odot$. The system would measure well over 200 $R_\odot$ across, but the size of the loser would remain nearly the same on account of its decreasing share of the total mass of the system. Another consequence would be the diminished radial velocity range predicted for the gainer, from 20 km s^{-1} at i = 80° to 8 km s^{-1} at i = 40°.

If, in spite of the antics of the loser, the gainer still is a main-sequence star, which is quite possible, we can estimate its properties: we should expect a star between B6 and B2, depending on its mass. Such a star should be more easily detectable in the ultraviolet, and it appears that it had indeed been detected. The first report came from Duvignau, Friedjung, and Hack (1979), who found evidence for it with the Copernicus and S 2/68 satellites. The object was at the limit of detectability for Copernicus, but some lines were identified, including the N V resonance doublet at 1240 Å. This identification as well as the general appearance of the spectrum in the region 1159 - 1254 Å suggested the resemblance to B 0 supergiants. The S 2/68 observations in the region 1400 - 1600 Å are rather confusing but do suggest a fairly early spectral type, more likely of higher luminosity than not. The Copernicus observations suggested a radial velocity range for the gainer of 12 ± 8 km s^{-1}. This value would be best compatible with i ≃ 50° and mass of the gainer m(g) = 6 $m_\odot$, but of course the uncertainty is too large. The observations failed to detect eclipses, which should be deeper in the ultraviolet.

Hack (1981) reports on her observations with the IUE: "The continuum clearly shows the presence of a hot companion and a reddening of about +0.30 [i.e., E(B-V) = 0.30 mag]; a very good fit of the observations is obtained with a composite spectrum formed by adding the flux of Alpha Cyg (A2 Ia) reddened for E(B-V) = 0.31 to the flux of Zeta Oph (O9.5 V, E(B-V)=0.31) reduced by a factor of 35. Hence, if the primary is an A-type supergiant, M_V = -7 or -8, ... the companion should be an O9 dwarf which at λ 1500 has about the same luminosity as the primary, but in the visual is about 100 times less luminous than the primary." Contrary to that, Schönberner and Drilling (1983) have found that the combination of a B2 Ib supergiant with an A supergiant which is 5 mag brighter in V provides a much better fit both for the continuum and the absorption lines. But it creates a puzzle how a B2 Ib supergiant can be much less luminous that the A supergiant. Schönberner and Drilling attempt to circumvent this difficulty by assuming that the secondary is not in thermal equilibrium because it is accreting matter from the loser. However, a high rate of mass transfer is not supported by any observations. Moreover, if it existed, an accretion disk would surround the gainer and luminosity predictions would much depend both on dM/dt as well as on the inclination of the disk with respect to the line of sight; we would quite possibly obtain a distinctly non-stellar flux distribution as the disk could easily dominate over the star's radiation.

The above fitting attempts are about the best we can do, but it is necessary to realize that this approach cannot yield the correct picture. The optically observed star is extremely hydrogen-poor and so is most likely the companion. Ordinary stars with solar-like composition cannot be used to represent their respective flux distributions. I would like to demonstrate my point with the aid of Fig. 2. This figure shows the flux distribution of υ Sagittarii obtained at the end of May, 1980, from my observations made nearly simultaneously with the IUE and the Lick Observatory ITS scanner at the 3m Shane telescope. The two scans do not match too well near 3200 Å, and I left a gap there, since neither instrument gives a reliable response in the vicinity of this wavelength. The mismatch does not seriously affect the overall picture of flux distribution. The color excess used is E(B-V)=0.25, and was obtained by eliminating the 2200 Å interstellar bump. The uncertainty of this value is about 0.05 mag, but a much larger margin of error is unlikely, so the actual fluxes are fairly well represented by my diagram.

The optical spectrum can be very well matched by two different models: One is a Kurucz (1979) model with a normal composition (N(H) = 0.9, N(He) = 0.1), an effective temperature of 11,000°K, and log g = 2.5. The other model shown is Klinglesmith's model with hydrogen reduced to N(H) = 0.06, N(He) = 0.94, an effective temperature of 10,000°K, and log g = 2.5 again (Klinglesmith 1971). The surface gravity has a negligible effect, and the effective temperatures and color excesses could be adjusted to provide an even better match. The helium-rich model postulates deep Balmer lines, while none are actually seen at the low resolution of the scan (about 7 Å). It is true that one could argue that the hydrogen lines are filled in by emission which shows at Hα, but a more decisive cause is no doubt the virtual absence of hydrogen in the star. Apart from that, both models represent the Paschen continuum equally well and ...

... They equally dismally fail shortward of the Balmer discontinuity, but each of them in a different way. Both postulate a huge Balmer jump, but there is very little of it in the star. Thus, it is not surprising that the models offer no guidance between the Balmer jump and about 2500 Å. The hydrogen-poor model then roughly represents the observed flux down to about 1500 Å, beyond which wavelength one has to postulate a sharply rising flux from the other component. On the other hand, the 11,000°K model does not require any additional source at short wavelengths; in fact, there is a deficiency of flux there! One can certainly argue that this model is not valid for a hydrogen-depleted star, and I can only counter by saying that it is just as much or as little valid as the combinations of two standard spectra discussed above.

Line blocking is very serious in the ultraviolet in the Kurucz model, and will be even more serious in the hydrogen-depleted model, since the absorption lines will be deeper. Quite possibly the alleged supergiant character of the hotter spectrum is due just to this line blocking. I am almost tempted to speak of the "alleged supergiant character of the alleged hotter spectrum." For we really do not know what the shape of flux distribution is for either star.

A powerful blow to a simple interpretation has now come from an observation made by Polidan with the Voyager spectrometer, which is sensitive down to the Lyman limit. The recorded spectrum (Figure 3) does show the sharp rise in flux between 1450 Å and 1250 Å, but it also shows an equally abrupt decline at 1100 Å. In this respect, this is a unique spectrum, since no other object shows it. An early B star of any luminosity class maintains high flux levels around 1100 Å. You will notice that Polidan uses a smaller value of the color excess (0.12 mag), but the interstellar reddening curve seems to be rather flat there, so interstellar reddening cannot be responsible for the abrupt drop of flux at 1100 Å.

In short, the character of the secondary component (the gainer) is far from known. What is most urgently needed above all is modern model stellar atmospheres, with line blocking taken into account, for stars with various degrees of hydrogen depletion, all the way to pure helium stars.

4. EXTREME HELIUM BINARIES AND BINARY STAR EVOLUTION

Careful IUE observations are highly desirable in order to establish: 1) the existence or absence of eclipses; 2) the radial velocity curve of the gainer, if observable.

Establishing the gainer's mass — directly from radial velocities velocities and/or indirectly from spectrophotometry — is very important for checking on the general model outlined here, and on evolutionary calculations for interacting binaries. If the present mass of the loser is near 1.5 $m_\odot$, then its initial mass must have been 10 - 11 $m_\odot$ (De Greve 1982). There is a puzzling discrepancy in the remnant masses at the end of case B between de Loore and De Greve on the one side, and Delgado and Thomas (1981) on the other: according to the latter authors, an initial mass of 9 $m_\odot$ yields, after mode B of mass transfer, a helium star of 2.0 $m_\odot$, while De Grève and De Loore give 1.66 $m_\odot$ as the remnant mass for a star initially of 10 $m_\odot$. But this does not change my argument: If the initial mass was 9 - 11 $m_\odot$ and is now 1.5 $m_\odot$, then 7.5 - 9.5 $m_\odot$ of gas left the loser — but only a fraction of that could have landed on the gainer, which according to our above estimates, should be about 3.6 - 6 $m_\odot$ now and almost certainly no more than 9 $m_\odot$, and naturally must have entered the mass transfer process with some decent mass of its own. The implication is that the process seems to be more a process of mass loss from the binary system than mass transfer between the components; and it may be that stellar wind plays a very significant role. There is currently a very extensive debate going on as to whether the mass transfer process is nearly conservative or not, and if the case of υ Sagittarii is well established, this would seem to be a powerful argument for strongly non-conservative processes.

We see that we still have a long way to go before we understand the helium-rich binaries to our satisfaction. But, if we improve our knowledge on these rather bizarre systems, we will also have a valuable test on the current theories of binary star evolution.

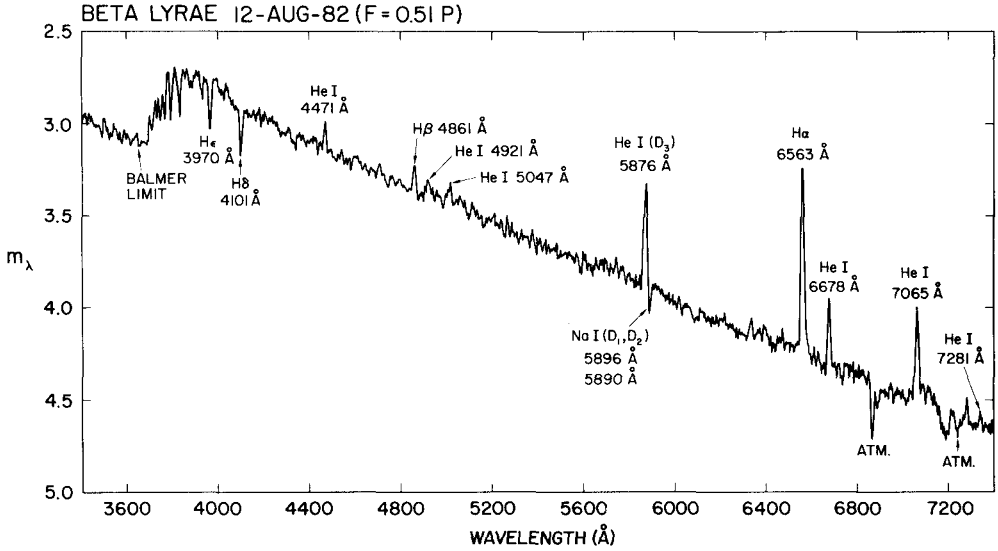

Fig. 1. - Optical scan of Beta Lyrae shows strong emission lines of HeI.

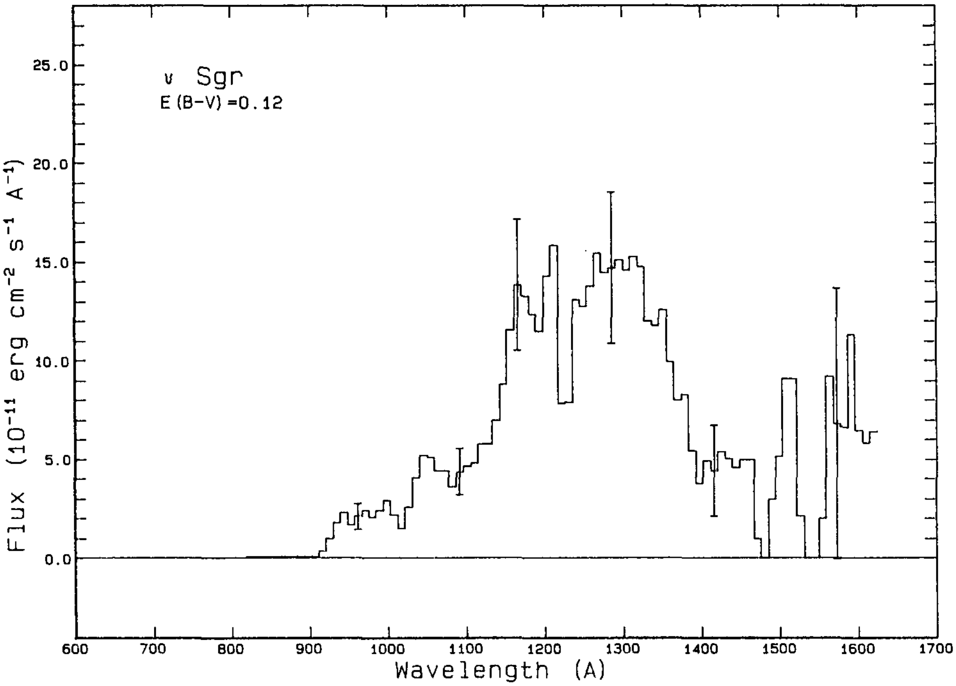

Fig. 3. Voyager scan of Upsilon Sagittarii shows no hot star flux.

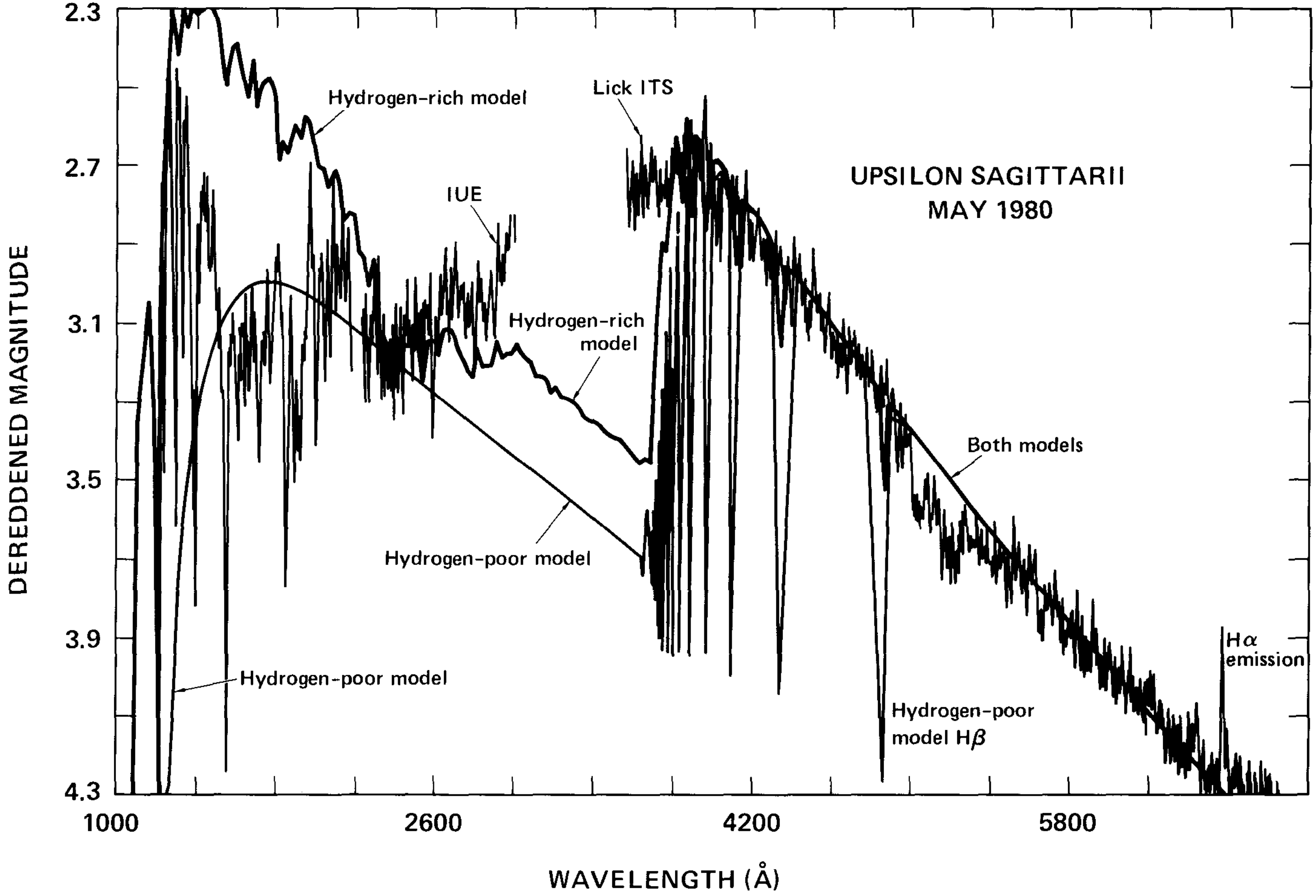

Fig. 2. - Flux distribution of Upsilon Sagittarii and two models.

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DISCUSSION

N.K. RAO: We looked at the ANS observations of the Upsilon Sgr during 1974-75. Some of the observations show that there was an eclipse with a depth of about 0.1 mag in the ultraviolet which coincides with the phase of Hiltner's earlier optical observations. The companion is of the spectral type B8, but it is probably a disk rather than a star. We also investigated the IS reddening, the IS atomic lines and the polarization and found that M_v is around -4 rather than -7. This has already been published (J. Ap. Astr. **6**, 101, 1985).