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ON THE NATURE OF UPSILON SAGITTARII[1]

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ABSTRACT

We present a new explanation for the nature and evolution of the extremely hydrogen-deficient binary υ Sgr which is consistent with all observational and theoretical facts. First, the system goes through a Case B mass exchange in which most of the hydrogen-rich envelope of a massive primary (5 to 14 $M_\odot$) is lost. The remaining envelope still contains about 50% hydrogen (by number), but is now of negligible mass, so that the star will evolve like a pure helium star. If its mass is between 1 and 2 $M_\odot$, the star will reach low surface temperatures and become a supergiant before the onset of carbon burning. This star (the original primary) will then fill its Roche lobe a second time, spilling its now helium-rich envelope over onto the secondary (Case BB mass exchange). We argue that υ Sgr is in this state at the present time, and that the visible star is an evolved helium star of about 1 $M_\odot$ with a degenerate carbon-oxygen core and a helium-burning shell which provides the high luminosity.

Key words: hydrogen-deficient binaries; binary evolution

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I. INTRODUCTION

Hellings et al. (1981) have proposed the following evolutionary status for the hydrogen-deficient binary υ Sgr. According to them, the system consists of a 13 $M_\odot$ primary and a 10 $M_\odot$ secondary. The primary is "the hydrogen exhausted core of a star which has evolved through phases of stellar wind mass loss during core hydrogen burning and eventually during core helium burning, and mass loss By Roche lobe overflow". The original mass of the primary was estimated to be between 40 and 50 $M_\odot$. Only Case B and Case C binary evolution were considered, neither of which is able to explain the observed low hydrogen abundance.

In this paper, we present a new, completely different interpretation of the nature of υ Sgr. Our main conclusions are as follows. We are now seeing a binary system in its second mass exchange, i.e., the primary, now a helium supergiant, has filled its Roche lobe a second time (Case BB mass exchange) after having lost nearly all of its hydrogen-rich envelope during an earlier, Case B, mass exchange. This provides a natural explanation for the unusual surface composition of the primary. The total mass of the system is much lower than that proposed by Hellings et al. (1981), and the initial mass of the primary was less than 14 $M_\odot$.

II. THE FACTS

First we want to summarize the relevant observational and theoretical facts. It is well known that υ Sgr is a supergiant ($M_V \approx -7$) with an effective temperature of about 10,000°K and very weak hydrogen lines ($W(H\gamma) = 0.5$ Å), that it is both a single-line spectroscopic binary and an eclipsing binary with a period of 138 days (Hack and Pasinetti 1963, Eggen et al. 1950). Hack and Pasinetti (1963) estimate that n(H)/n(He) = 0.025 on the basis of a coarse analysis of the spectrum. How dangerous such an analysis can be is illustrated convincingly by Fig. 3 of Wallerstein et al. (1967), in which theoretical Hγ profiles based on model atmospheres computed by Böhm-Vitense are given for T_{eff} = 10,000°K, log g = 2, and n(H)/n(He) = 0.0005, 0.005, 0.05, 0.5, and 5. According to these profiles, Hγ is stronger for n(H)/n(He) = 0.025 than it is for a normal hydrogen abundance!

Comparison of the Hγ profile given by Hack and Pasinetti (1963) with Fig. 3 of Wallerstein et al. (1967) yields n(H)/n(He) < 0.0005 for υ Sgr. This is very similar to the hydrogen abundance found by Wallerstein et al. (1967) for the single-line spectroscopic binary KS Per (HD 30353), which is not surprising since these stars have similar effective temperatures, surface gravities, and Hγ profiles. The primaries of both of these systems can therefore be considered to be extreme helium stars. In contrast to the apparently single extreme helium stars, they show nitrogen to be much more overabundant than carbon, indicating that CNO-processed material has been exposed at the surface (Hack and Pasinetti 1963, Danziger et al. 1967).

Observations made by spacecraft show that most of the radiation shortward of 1700 Å comes from a hot companion. Hack et al. (1980) adopt a spectral type of O9V for the secondary on the basis of IUE observations. However, inspection of the IUE spectral atlas of Wu et al. (1981) shows that the spectrum of θ Ara (B2Ib) is a much better match to that of υ Sgr shortward of 1700 Å than that of any other star in the atlas (Drilling and Schönberner 1982). This is consistent with the earlier conclusion of

Duvignau et al. (1979) that the spectrum of the secondary was similar to that of a B0–B3 supergiant based on Copernicus and TD1 satellite observations.

If the hot component does have the spectrum of an early B-type supergiant, then its visible spectrum must be 5 magnitudes fainter than that of the primary (Drilling and Schönberner 1982). This is supported by the light curve of Eggen et al. (1950), which shows the visual magnitude of the secondary to be 3 magnitudes fainter than that of the primary if the eclipses are total, and explains why spectral lines due to the secondary have never been observed in the visible spectrum. The hot component must therefore be much less luminous than a normal B-type supergiant.

Duvignau et al. (1979) have concluded that $M_p/M_s < 0.5$ from the smallness of the radial velocity variations in the ultraviolet. Since the mass function for υ Sgr is 1.68 $M_\odot$, it follows that $M_p \sin^3 i < 1.9\ M_\odot$, so that even for $i=60^\circ$ the mass of the primary is less than 2.9 $M_\odot$. The primary must therefore be a highly evolved object to account for its high luminosity ($L = 50{,}000\ L_\odot$ for B.C.= 0 according to Duvignau et al. 1979). On the other hand, we have $M_s \sin^3 i < 3.8\ M_\odot$, much too small for the secondary to be an early B-type supergiant, or even an O9 main sequence star. However, because L/M determines the spectral appearance for a given temperature, a star of low mass and low luminosity with an extended envelope can mimic the spectral appearance of an early B-type supergiant. If we take $M_V = -3$ and B.C.= −1.5 for the secondary, we get $L = 5000\ L_\odot$. In order to have the same L/M as an early B-type supergiant ($\approx$ 2500 times solar), the mass of the secondary would have to be about 2 $M_\odot$, which is consistent with the above discussion. We therefore conclude that the hot component of υ Sgr is neither an early B-type supergiant nor a main sequence star, but rather a lower mass object with an exte , envelope, i.e. a star which is not in thermal equilibrium because of the accretion of matter lost by the primary (Kippenhahn and Meyer-Hofmeister 1977; Packet and de Greve 1979). This star may have a distorted shape due to non-spherical accretion, but the existing light curves are not detailed enough to determine whether or not this is the case.

Coming back to the primary, we want to emphasize that it is hard to believe that it is a helium supergiant of 13 $M_{\odot}$ as suggested by Hellings et al. (1981) for a number of reasons. According to Stothers and Chin (1977), helium stars of 8 to 15 $M_{\odot}$ are able to reach low surface temperatures at the end of carbon burning, but only if there is no neutrino emission! Even if this were the case, their visual brightness would be too large $M_V \approx -9$. The corresponding models of Paczynski (1971) do not evolve to low surface temperatures at all. We therefore conclude that the suggestion of Hellings et al. (1981) concerning the mass of the primary is in conflict with theory and observation.

Furthermore, neither Case B nor Case C mass exchange can expose processed material with a sufficiently low hydrogen abundance to satisfy the observations, even if we accept the value n(H)/n(He) = 0.025 given by Hack and Pasinetti (1963). Case B mass exchange stops when matter with X = 0.2 is exposed (de Greve and de Loore 1976). For Case C, the final hydrogen content of the envelope is also $X \approx 0.2$ as a result of the dredge-up phenomenon which occurs in all stars with core masses $\gtrsim 0.8\ M_{\odot}$ just prior to hydrogen shell re-ignition (Lauterborn 1970, Kippenhahn et al. 1965). Any further mass loss is governed by the nuclear timescale of the hydrogen-shell-burning primary, and no further changes in the surface composition are possible. In both cases, the radius of the region where hydrogen has been totally depleted is at all times much smaller than the Roche radius.

III. THE EVOLUTIONARY STATE OF UPSILON SGR

In the previous section we have shown that the present appearance of υ Sgr cannot be the result of a single mass exchange. We can resolve this riddle by assuming that we are now seeing the second mass exchange, and that the primary lost nearly all of its original hydrogen-rich envelope during a first, Case B, mass exchange. The first mass exchange stops when $X = 0.2$ is reached at the surface. The primary then shrinks and ends up near the helium main sequence (Kippenhahn and Weigert 1967, de Greve and de Loore 1976). The border between the pure helium layers and the somewhat hydrogen-rich layers, i.e., the position of a weak hydrogen-burning shell, is now at $M_r/M \approx 0.9$. The primary will therefore evolve like a pure helium star.

It is well known that helium stars between 1 and about 2.5 $M_\odot$ are able to expand to a supergiant configuration during the helium shell-burning phase, reaching low surface temperatures ($T \lesssim 10{,}000^\circ K$) prior to the onset of core carbon burning (Paczynski 1971, de Greve and de Loore 1977). Note that now layers of nearly pure helium are expanding to large radii, and that the primary is now able to fill its Roche lobe a second time, first spilling any remaining hydrogen-rich material and then nearly pure helium onto the secondary (i.e. the Case BB mass exchange of Delgado and Thomas, 1981). At $10{,}000^\circ K$ these helium supergiants have radii of 40 to 60 $R_\odot$, which is comparable to the present size of the Roche lobe of υ Sgr (60 $R_\odot$ for $q = 0.5$ and $\sin i = 1$).

This evolutionary scenario is consistent with the observations. It predicts the observed abundances for the primary, a mass between 1 and 2.5 $M_\odot$, and a luminosity between 10,000 and 60,000 $L_\odot$, depending on the initial mass and evolutionary state. The most likely mass for the primary is around 1 $M_\odot$ because Delgado and Thomas (1981) show that a helium star of 2 $M_\odot$ looses half of its mass in only 10,000 years. This rapid phase of mass transfer is followed by a much slower one which changes the mass only marginally, and this is probably the state which we now observe. In any case, the interior of the visible component of υ Sgr must consist of an inert, condensed carbon-oxygen core surrounded by a helium-burning shell which provides the luminosity (Paczynski 1971; Biermann and Kippenhahn 1971). This star will evolve into a massive white dwarf while the secondary is still near the main sequence. A third mass transfer may occur when the secondary evolves away from the main sequence, but due to the large separation of the components this will probably not happen before the end of core helium burning (Case BBC of Delgado and Thomas, 1981).

We find from the theory of Case B mass exchange that the original mass of the primary must have been between 5.6 and 14 $M_\odot$ (de Loore 1980). Therefore the primary must have lost between 5 and 12 $M_\odot$. Because the present mass of the secondary is less than 4 $M_\odot$, most of this mass has probably left the system. In other words, we have a typical example of binary evolution with a substantial loss of total mass (and total angular momentum), at least during the first Roche lobe overflow. Therefore, we cannot say anything about the period of revolution before the Case B mass transfer. The loss during the Case BB mass exchange cannot, however, exceed about 1 $M_\odot$, so that the period of revolution after the Case B mass transfer cannot be greatly different from what it is now (138 days). De

Greve and Vanbeveren (1980) find that of the 40 systems believed to be the result of Case B mass transfer, only 1 has a period longer than 24 days. It is not surprising then that systems like υ Sgr are rare. In fact, only two other objects are known which are similar to υ Sgr: KS Per (HD 30353), with a period of 360 days, and LSS 4300 (HDE 320156), for which the period is not known. All three of these objects have very similar effective temperatures (Drilling and Schönberner 1982).

IV. CONCLUSIONS

We have presented an explanation for the evolution of υ Sgr which is consistent with all known observational and theoretical facts. The basic idea is that we are now seeing a second, Case BB, mass loss by a primary which has already lost most of its mass in a previous, Case B, mass exchange. An interesting prediction of this theory is that the hot secondary should also be helium-rich. A definite statement concerning the shape of the secondary or the existence of a (thick) accretion disk may be possible when a more accurate light curve becomes available. Finally, the following question needs to be answered: Why do we not observe Case BB binaries with higher effective temperatures (for the primaries)? De Greeve and Vanbeveren (1980) find that roughly 10% of the systems believed to be the result of Case B evolution have primaries of 1 to 4 $M_\odot$. Because most of these stars have orbital periods of less than 25 days, they should go through Case BB mass loss at much higher effective temperatures than υ Sgr. A possible explanation may be that due to their small separations, these systems become contact binaries.

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