THE EVOLUTIONARY STATUS OF THE SECONDARIES OF CATACLYSMIC BINARIES

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ABSTRACT

It is shown that the secondary components of cataclysmic binaries with orbital periods of less than ~10 hours are indistinguishable from ordinary low-mass main-sequence stars and that, therefore, they are essentially unevolved. On the other hand, it is shown that, depending on the mass ratio of the progenitor system, the secondary of a cataclysmic binary could be significantly evolved. The fact that nevertheless most of the observed secondaries are essentially unevolved can be accounted for by assuming that the probability distribution for the initial mass ratio is not strongly peaked towards unity mass ratio.

I. INTRODUCTION

In a number of recent observational studies of cataclysmic binaries (hereafter CB's), in particular of BV Cen (Vogt and Breysacher, 1980; Gilliland, 1982), AE Aqr (Patterson, 1979; Chincarini and Walker, 1981), DQ Her (Smak, 1980; Young and Schneider, 1980, 1981) and U Gem (Wade, 1979, 1981) it has been found that the corresponding secondary is oversized for its mass when compared with the theoretical main-sequence mass radius relation. Based on this observation it has been concluded that the secondary is evolved. On the other hand, at least in the case of DQ Her and U Gem the mass of the secondary is so small that normal nuclear evolution cannot result in any significant evolutionary effects over the age of the universe. Therefore, if these stars are in fact evolved, they must have undergone an unusual evolution. Thus, with regard to the evolutionary history of a CB, it is essential to know whether its secondary is evolved or not. It is the purpose of this paper to discuss briefly the observational and theoretical evidence for evolved secondaries.

II. DISCUSSION OF THE OBSERVATIONAL DATA

Using published observational data, a mass radius and a mass lumino-

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sity diagram (hereafter MR and ML diagram respectively) for the secondaries of CB's have been constructed. In order to avoid a circular argument regarding the evolutionary state of these stars, only systems for which the mass of the secondary can be inferred without assuming it to be on the main sequence have been used. After a critical review of the available observational data, the following systems have been taken into account for the MR diagram: BV Cen, AE Aqr, RU Peg, EM Cyg, Z Cam, SS Cyg, RW Tri, DQ Her, U Gem, LX Ser, AM Her, HT Cas and Z Cha. The ML diagram is derived from the MR diagram by computing the corresponding luminosity L from the radius R and the effective temperature T_{eff} of the secondary: T_{eff} in turn has been determined from the known spectral type using an observationally calibrated relation between the spectral type and T_{eff} given by Popper (1980). Acceptable spectral types for the secondary are available for all but two, namely LX Ser and HT Cas, of the above-mentioned systems. The resulting MR and ML diagrams have recently been published (Ritter, 1982 a). Furthermore, a preliminary version of the MR diagram has been discussed earlier (Ritter, 1980). A more detailed discussion of the observational data and of the selection criteria as well as the justification of the values for the parameters which have been adopted for a particular system will be published elsewhere (Ritter,1982 b)

Conclusions on the evolutionary status of the secondaries of CB's are derived from comparing the MR and ML diagrams of CB's with the corresponding diagrams of the theoretical low-mass main sequence (Copeland, Jensen and Jørgensen, 1970; Grossman, Hays and Graboske, 1974) and of observed low-mass main-sequence stars (Popper, 1980). The main results of such a comparison (Ritter, 1980, 1982 a) can be summarized as follows:

a) The MR diagram

When comparing the MR diagram of the secondaries of CB's with theoretical MR relations, it turns out that, in fact, a number of secondaries have a radius which is larger by about $\Delta \log R \approx 0.1$ than the radius of the theoretical models with the same mass. However, when compared with the MR diagram of observed low-mass main-sequence stars (Popper, 1980), the two sets of data match perfectly within the observational errors. Thus, in the MR diagram, the secondaries of CB's with orbital periods of less than about 10 hours are indistinguishable from normal low-mass main-sequence stars. The discrepancy between the observed and the theoretical MR relations must be attributed to inadequacies of the theoretical models.

b) The ML diagram

The ML diagram is a much more sensitive probe of the evolutionary status of a star than the MR diagram. Therefore, evoluionary effects which might escape detection in the MR diagram might at the same time become visible in the ML diagram. However, when the ML diagram of the secondaries of CB's is compared with the ML diagram of the observed low-mass main-sequence stars, one finds again that the two sets of data match perfectly within the errors. The agreement is even better than one could have expected regarding the way the luminosities of the secondaries have been determined. The agreement between the theoretical and the observed data is not perfect but much better than in the case of the MR diagrams.

The conclusion to be drawn from these comparisons is that the secondaries of CB's with orbital periods of less than about 10 hours are indistinguishable from ordinary low-mass main-sequence stars. This, in turn, means that these stars are essentially unevolved. On the other hand, this does not imply that they are zero-age main-sequence stars.

III. THEORETICAL CONSIDERATIONS

Despite the fact that some of the secondaries of CB's have a very low mass, the observation that these stars are essentially unevolved nevertheless calls for a theoretical explanation. The reason for this is that the standard theory for the formation of CB's allows for rather strongly evolved secondaries even of low mass (Ritter, 1982 a). This conclusion is based on the following theoretical considerations:

a) The Mass Loss of the Secondaries

If the standard theory for the formation of CB's is correct, then most of the secondaries must have lost a significant fraction of their mass during the formation of the CB's. This is seen from the following argument: let $M_{1,i}$ and $M_{2,i}$ be the initial masses of a CB progenitor on the main sequence. As a result of the formation of the CB, a fraction f of the mass of the primary ends as a white dwarf of mass $M_{WD} = M_{1,f} = f \cdot M_{1,i}$. Because CB's are secularly stable against mass transfer, the mass, $M_{2,f}$ of the seconcary has to be smaller than that of the white dwarf primary, i.e. $M_{2,f} \lesssim M_{1,f} = M_{WD}$. This in turn implies that the secondary, in the course of its evolution, must have lost the mass $\Delta M_2 = M_{2,i} - M_{2,f} = M_{2,i}\ (1-f.q_i/q_f)$, where $q_i = M_{1,i}/M_{2,i}$ and $q_f = M_{1,f}/M_{2,f}$. Since for reasons of secular stability q_f 1, the secondary can keep its original mass only if $q_i \gtrsim f^{-1}$. Depending on $M_{1,i}$, f is in the range 0.2 to 0.5. Thus mass loss from the secondary can only be avoided for rather large values of the initial mass ratio q_i.

b) The Possibility of Evolved Secondaries

If the initial mass ratio q_i of the progenitor of a CB is not too far from unity, the secondary has spent a significant fraction of its main-sequence life-time when the binary enters the common-envelope phase. From the mass luminosity relation for main-sequence stars, i.e. $L = \text{const.}\ M^{\alpha}$, the fraction of the main-sequence life-time which the secondary can spend before the CB is formed, is estimated to be $\varepsilon \approx q_i^{\,1-\alpha}$. Since the systems which produce the most evolved secondaries, i.e. those with $q_i \approx 1$, are also those where the secondary suffers the largest mass loss, there is the possibility that some of the secondaries of CB's now essentially consist of the former hydrogen burning central region and even may expose nuclear processed matter at their surface. In fact, the secondaries of CB's are like the remnants of a Case A mass transfer (see e.g. Horn, Kriz and Plavec, 1970). Because $\alpha \approx 3.5$, no significantly evolved secondaries result if $q_i \gtrsim 2$.

c) The Probability of Evolved Secondaries

Since rather highly evolved secondaries are theoretically possible, the fact that the observed secondaries are essentially unevolved calls for an explanation. As has been shown above, the secondary is the more evolved the closer the initial mass ratio is to unity. Thus the absence of significantly evolved secondaries could be accounted for by assuming that systems with $q_i \approx 1$ are very rare. In fact it can be shown that it is already sufficient if the probability distribution of q_i is not strongly peaked towards unity mass ratio (Ritter, 1982 a).

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DISCUSSION FOLLOWING H. RITTER'S TALK

SUGIMOTO: What is the mechanism to strip off the mass from the scondary?

RITTER: I can't answer this question because our knowledge about common envelope is probably nearer to speculation than to actual knowledge, so this is only a boundary condition for any theory which wants to explain these objects, it has also to account at least in some cases, for a significant loss in the mass of the secondary star. What the mechanism is, I don't know.

SHAVIV: What is the average progenitor mass for the secondary you have?

RITTER: I have not estimated the typical progenitor mass, the argument I have made is essentially independent of that.

FINZI: Doesn't the space distribution of Cataclysmic Variables in the galaxy lead to significant upper bounds for the masses?

RITTER: Rather long ago it has been claimed by Kraft that the space distribution is similar to that of W Ursa Majoris stars, so I don't know whether one can really draw reliable conclusions from this space distributions because we really don't look very far when we observe Cataclysmic Variables. The typical distance is a few hundred parsecs and with the few novae we look at a kiloparsec or so, so I would hesitate to draw conclusions from statistical arguments.

EGGLETON: The diagram that you showed of the observed radii and masses, superimposed on the theoretical radii and masses, I thought you were going to say how good the theory was to give such a good agreement, but you drew a line between them and seemed to show that the agreement was not good. Were those 1σ error bars or 2σ error bars?

RITTER: The error bars for the mass-luminosity diagram of the visual binary components are 2σ error bars and Popper is very conservative. My error bars are rather more boundaries and probability ranges and not proper error bars.

EGGLETON: But one sees two observed stars there which disagree more with the trend than I think even the theoretical models do and this may well be evidence for instrinsic variability such as different compositions and so on. A variation in those parameters, such as the composition could presumably move things around, I would see the theoretical things as also having a consideraboy greater scatter and really I would have thought, that was a good agreement.

SHAVIV: I would like to mention that most of this separated low mass main sequence stars are peculiar in terms of magnetic activity and so on, so it is not clear a priori that they are quite main sequence stars of the type our programs calculate. Recently I have carried out a calculation with Art Cox, trying to fit a single point and we found that it was necessary to reduce the mixing length to scale height ratio to something like 10^{-3} to get anywhere near a good agreement between the mass, the luminosity and the radius of that star, assuming no evolutionary effects.

EGGLETON: Mixing length is less important for these low mass stars, but I am suggesting that metallicity may still be fairly important.

RITTER: I can only answer that it is because these low mass stars are probably not the models we compute, that it is much better probably to compare observed stars with other observed values, rather than theory with observations.