EVOLUTION OF EARLY-TYPE CONTACT BINARIES

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1. SV CENTAURI AS AN EVIDENCE OF MASS EXCHANGE

SV Centauri is an early-type contact binary for which detailed physical data have been obtained from observations (Wilson and Starr 1976). The orbital period is $p = 1.659$ days and the separation is $a = 16.1\ R_\odot$. The radii of component Stars A and B are, respectively, $R = 7.2$ and $6.9\ R_\odot$ so that they are in overcontact. The masses and the luminosities are $M = 11.1$ and $9.3\ M_\odot$, and $L = 2830$ and $10900\ L_\odot$ for Stars A and B, respectively. The more massive Star A is called the primary star but its luminosity is fainter than Star B. This implies that it is in the phase of rapid mass transfer and mass is outflowing from Star A. Indeed one of the most interesting and important points

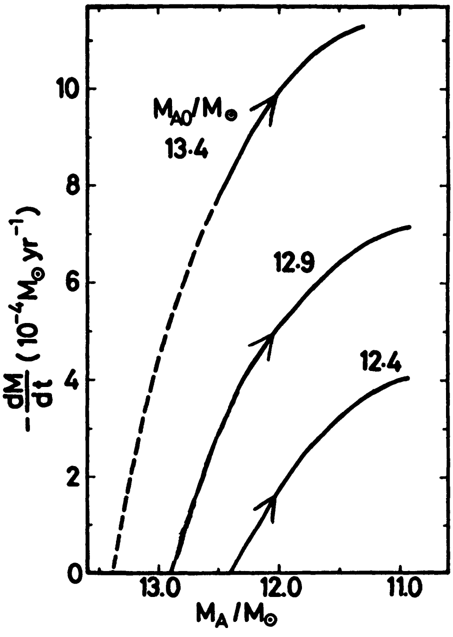

Fig. 1. —— Changes in the rate of mass transfer are shown against the mass of Star A. Three different cases for its initial mass. For the dashed part of the curve, the computed results are not smooth enough, because advance guesses for the rate were not sufficiently accurate. However, it seems to affect but little the behavior in later stages.

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of this system is that the rate of period change is measured to be dP/dt = -9.4×10^{-8} (Irwin and Landolt 1972) which corresponds to the mass transfer rate of $dM_A/dt = -4 \times 10^{-4}\ M_\odot\ yr^{-1}$.

Recently, Nakamura, Saio, and Sugimoto (1978) computed a model for this binary system by using a stellar evolution code in which included are the effects of mass loss as well as mass acceptance. They assumed the conservations of mass and angular momentum during the mass exchange. Only one parameter of the model is at our disposal, which they chose to be the initial mass of Star A, i.e., M_{A0}. Assuming its value they followed evolution of both stars until the mass of Star A was reduced down to its present value, i.e., to $M_A = 11.1\ M_\odot$, as a result of overflow from its critical Roche lobe.

In constructing such models Nakamura et al. (1978) computed three cases for the initial mass of Star A, i.e., for M_{A0} = 12.4, 12.9, and 13.4 $M_\odot$. The last one was not published in their paper, because it resulted in too high rate of mass transfer. In Figure 1 we reproduce the time changes in their mass transfer rates for all of the three cases. The case of $M_{A0} = 12.4\ M_\odot$ fits well with observations both in the HR diagram and in the rate of mass transfer, as was discussed in detail by Nakamura et al. (1978). This implies that SV Cen can be a compelling evidence supporting general idea of mass transfer during the evolution of binary stars.

2. INCREASE IN RADIUS OF MASS ACCEPTING STAR

Of particular importance and interest is the evolution of the mass accepting Star B. As a result of rapid mass acceptance in large amount, the radius and the luminosity of Star B increase. Nakamura et al. (1978) computed evolution of the mass accepting Star B only for the cases of M_{A0} = 12.4 and 12.9 $M_\odot$. At the stage of $M_B = 9.3\ M_\odot$, its radius is 6.0 and 8.1 $R_\odot$, respectively. For the case of $M_{A0} = 13.4\ M_\odot$, we estimate its radius to be 10 $R_\odot$ by extraporating in log R - log (dM/dt) plane. Such large difference in the radii of Star B is ascribed mainly to the difference in the rates of mass transfer as discussed by Kippenhahn and Meyer-Hofmeister (1977) and by Neo, Miyaji, Nomoto, and Sugimoto (1977). The difference in the rates of mass transfer is ascribed to the difference in the sizes of the initial critical Roche lobe, which are $R_{cr,A0}$ = 7.3, 7.8, and 8.5 $R_\odot$, for M_{A0} = 12.4, 12.9, and 13.4 $M_\odot$, respectively. Here we see how large difference in the mass transfer rates results from a relatively small difference in the initial Roch lobes.

The size of the critical Roche lobe for Star B is $R_{cr,B} = 5.9\ R_\odot$ at the present stage of $M_B = 9.3\ M_\odot$. In the case of $M_{A0} = 12.4\ M_\odot$ Star B will be marginally accommodated within its critical Roche lobe, and the mass transfer will continue conservatively. In the case of M_{A0} = 13.4 $M_\odot$, on the other hand, Star B will not accept matter any more after its radius exceeds $R_{cr,B}$ appreciably. Then the mass overflowing from Star A must escape from the binary system and the mass transfer will become non-conservative. Here we notice that only a small difference in the initial conditions leads to large difference in the mode of mass transfer, conservative or non-conservative.

3. FATE OF CONSERVATIVE MASS EXCHANGE

Conservative mass exchange in a binary system has been studied extensively in these ten years. In our case of $M_{A0} = 12.4\ M_\odot$ (or less), the mass transfer commences when hydrogen is still left in the convective core. It continues until a stage when the mass ratio is almost reversed. After that the mass transfer continues with the nuclear time-scale as Star A evolves and expands. Finally almost all of the hydrogen-rich envelope is transferred from Star A to Star B. Now Star A is almost a helium star of mass about $M_A \simeq M_{A0}/4$. Then it evolves, makes a supernova explosion, and leaves a neutron star.

The separation between the components increases after the reversal of the mass ratio. If the initial mass ratio was unity, the separation and the period before the supernova explosion is $a \simeq 5.2 a_0$ and $P \simeq 12 P_0$, where a_0 and P_0 are their initial values. For our model of $M_{A0} = 12.4\ M_\odot$ we have $a \simeq 60\ R_\odot$ and $P \simeq 12$ days, when $M_A = 3.1\ M_\odot$. When a supernova explosion takes place its separation becomes somewhat wider. The system would become an X-ray binary. Thus X-ray binary of relatively long orbital period seems to have been born as a result of the conservative mass exchange.

4. NON-CONSERVATIVE MASS EXCHANGE AND SHRINKAGE OF SEPARATION

When the initial separation is somewhat large as in the case of our model of $M_{A0} = 13.4\ M_\odot$, the mass transfer will become non-conservative. Such situation has already been considered by Flannery and Ulrich (1977). However, their discussions were limited only to early stages of non-conservative mass exchange during which the mass of the primary star is reduced from 14.4 to 13.5 $M_\odot$. Therefore, it is well worth extending them into the later stages.

For such discussion, we have to know how much angular momentum is carried away with a unit mass of escaping matter. We have such information only for particles which are ejected from the second Lagrangian point. Though, the escaping matter is not the particle but the gas, its flow will soon become supersonic, which could be well assimilated by motion of a particle. The angular momentum carried away with a unit mass of matter is denoted by $\ell \omega a^2$, where ω is the orbital angular velocity. According to computations of particle trajectories (Nariai 1975; Flannery and Ulrich 1977), the value of ℓ is about 1.7 irrespective of mass ratio of the binary system. The orbits of the binary stars are assumed to be circular, because the circular orbits will be recovered by tidal interaction.

The total orbital angular momentum is ωa^2 times the reduced mass of the system, and the loss of the angular momentum is described by

$$\frac{d}{dM_A}\left(\frac{M_A\,M_B}{M_A+M_B}\,\omega a^2\right) = \ell\omega a^2. \qquad (1)$$

Here M_A is decreasing by mass loss while M_B stays constant. With the help of the Kepler's third law, equation (1) is integrated to yield (Nariai and Sugimoto 1976)

$$\frac{a}{a_0} = \frac{M_A+M_B}{M_{A0}+M_B}\left(\frac{M_A}{M_{A0}}\right)^{2\ell-2} \exp\left(-2\ell\,\frac{M_{A0}-M_A}{M_B}\right). \qquad (2)$$

Here we notice that the effect of angular momentum loss brings the component stars very close each other when (M_{A0} $-M_A$) is comparable to or larger than M_B. Let us consider the case of $M_{A0} \simeq M_B$. Because the mass loss from Star A is unstable, it will continue until the hydrogen-rich envelope is almost stripped off. If we use the approximate relation of $M_A \simeq M_{A0}/4$, equation (2) yields the value as small as $a/a_0 = 7.0 \times 10^{-3}$ for $\ell = 1.7$. A system similar to SV Cen but with a little longer orbital period, i.e., the case of $M_{A0} = 13.4\ M_\odot$ corresponds to such case. For a system considered by Flannery and Ulrich (1977), i.e., for $M_{A0} = 14.366\ M_\odot$ and $M_B = 5.634\ M_\odot$, we obtain $a/a_0 = 1.54 \times 10^{-4}$ for $M_A = 4\ M_\odot$. If these are the case, Star B can not be accommodated within its critical Roche lobe and will be dissipated by or will coalesce with a compact star.

Thus our conclusion is somewhat paradoxical. When the initial separation between the component stars is relatively narrow, they will be well separated even after the mass transfer. On the contrary, when it is relatively wide, they will coalesce each other.

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DISCUSSION FOLLOWING SUGIMOTO AND MIYAJI

Shu: An important effect left out in your calculations may be the back pressure of the common envelope. Have you considered the modulation on the mass transfer/loss rate due to this back pressure? In particular, have you considered the possibility that it might stop the mass transfer/loss altogether?

Sugimoto: I have not computed the effect of the back pressure, but I think it is negligible because of the following reasons. Almost all of the nuclear energy released in the mass losing star is absorbed in the deep interior where the temperature is about 1×10^7K. It is consumed in pushing out the outflowing matter against the entropy gradient, and it is necessary to keep the stellar radius as small as its Roche lobe. This implies that the interior of the star is greatly out of thermal equilibrium. If the mass outflow should stop, the star would expand greatly and it would overcome the back pressure. The energy involved in the mass outflow of the present model is of the order of the thermal energy of the whole star, which is much greater than the energy contained in the common envelope. Therefore, it will not be the common envelope but the thermal disequilibrium of the interior that determines the mass outflow.

Wilson: I suggest RT Sculptoris and V 701 Scorpii as other systems whose evolution would be interesting to model. RT Scl is in the rapid phase before mass ratio reversal. V 701 Sco is also in the rapid phase, only slightly after mass ratio reversal.

Sugimoto: Thank you for this information. It will be interesting to try to construct their models. From the standpoint of computational techniques, it is now easy to do so.

Webbink: I would like to endorse the remark by Frank Shu regarding the importance of back pressure once the secondary reaches contact. The presentation I have scheduled for Friday morning illustrates just this point.

Sugimoto: The effect of the back pressure may be important when the degree of thermal disequilibrium is very small in the deep interior of the star as in the case of W UMa stars. If you insist it to be important even in our case of a large thermal disequilibrium of the interior, please make clear the physics involved, when you read your paper.