NON-CONSERVATIVE MASS EXCHANGE AND ORIGIN OF X-RAY CLOSE BINARIES

Daiichiro Sugimoto and Shigeki Miyaji
Department of Earth Science and Astronomy, College of General Education, University of Tokyo, Tokyo 153, Japan

1. TWO TYPES OF X-RAY BINARIES

Recently, masses of component stars have been determined for many X-ray close binaries (XCBS). For relatively well determined sources the masses of X-ray components are plotted against the masses of their optical components in Figure 1 and their orbital periods are summarized in Table 1 (Cowley 1977; Bradt, Doxsey, and Jernigan 1979; Wheeler 1978; and references quoted therein). Cowley (1977) prepared a table and noticed that there are two distinct types of XCBS. The Type I XCBS consists of an X-ray star and an early type star more massive than about 12 $M_\odot$. On the contrary, the Type II XCBS consists of an X-ray star and a star less massive than about 2 $M_\odot$. As seen in Figure 1, there is not any distinct intermediate type for which the mass of the optical component lies in the range of about 2-12 $M_\odot$. The aim of the present paper lies in interpreting the origin of these types of XCBS on the bases of the conditions for the formation of a neutron star and of mass exchange in close binary systems.

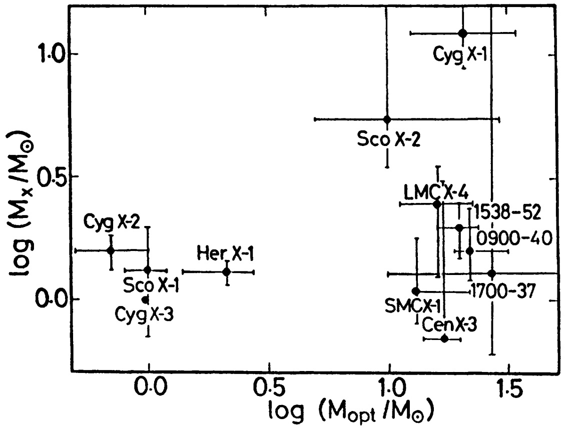

Fig.1. — Masses of X-ray components are Plotted against their optical components.

TABLE 1.— ORBITAL PERIODS

Source	P_{orb} (days)
Type I	
SMC X-1	3.89
LMC X-1	1.41
0900-40	8.97
Cen X-3	2.09
1538-52	3.73
Sco X-2	7.85
1700-37	3.41
Cyg X-1	5.60
Type II	
Sco X-1	0.79
Her X-1	1.70
Cyg X-3	0.20(16.9)
Cyg X-2	11.17(0.86)

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2. CONSERVATIVE MASS EXCHANGE AND TYPE I XCBS

In a separate paper presented to this symposium (Sugimoto and Miyaji 1979), which will be referred to as SM, it was discussed that a Type I XCBS is produced from an early-type contact binary as a result of conservative mass exchange. However, the resultant XCBS was shown to have a relatively long period. Such discussion is generalized to include different initial conditions. We denote the mass of the component stars A and B by M_A and M_B ($M_{A0} > M_{B0}$), respectively. The total mass of the system is $M_t \equiv M_A + M_B$ which is conserved. Here and hereafter the subscript 0 denotes its initial value. As the mass is transferred from Star A to Star B, the separation changes. It reaches the smallest value when $M_A = M_B = M_t/2$. The stage just before the supernova explosion of Star A will be denoted by the subscript 1. At this stage the hydrogen-rich envelope of Star A has been almost stripped off and we approximate $M_{A1} = M_{A0}/4$.

Even at the stage of the smallest separation, Star B should be accommodated within its Roche lobe. This condition is transformed into the condition for the period at the pre supernova stage as where

$$(P_1/\mathrm{day}) > \frac{11.2}{(3 + x)^3 \ (1 - x)^3} \ f^{3/2}(M_t/M_\odot) \ , \qquad (1)$$

$x \equiv M_{B0}/M_t$ is the initial mass fraction of Star B and $\underline{f}$ is the ratio of radius to mass in solar units for main-sequence stars. For resonable ranges in $x = 0.2 - 0.5$ and $M_t/M_\odot > (12 - 20)$, condition (1) yields $P_1 > (4.7 - 12)$ days, respectively. After the supernova explosion the period becomes somewhat longer. As far as Type I XCBS's in Table 1 are concerned, this condition is not satisfied though it is marginal for 0900-40. Therefore we have to seek another interpretation for the origin of such XCBS.

3. NON-CONSERVATIVE MASS EXCHANGE AND ORIGIN OF TYPE I XCBS

What happens if the initial separation is much wider than those discussed in the preceding section? In such case the mass transfer becomes very rapid and non-conservative as was discussed in SM. Then the component stars of early-type contact binary come so close each other that they will dissipate or coalesce.

Here, we will consider how large initial separation is required in order to avoid the coalescence. We will consider the case of Cen X-3 as a typical example. Its history is illustrated in Figure 2. The mass of its optical component Star B stays almost constant, which we take $M_B = 17\ M_\odot$ (Cowley 1977). In order to avoid the excessive closing up of the stars, we assume that the initial mass of Star A was close to but a little larger than M_B, i.e., $M_{A0} = (17 + \varepsilon)M_\odot$. After non-conservative mass exchange, the core of Star A is left whose mass is $M_{A1} = M_{A0}/4 = 4.25\ M_\odot$. From equation (2) of SM with $\ell = 1.7$ we obtain

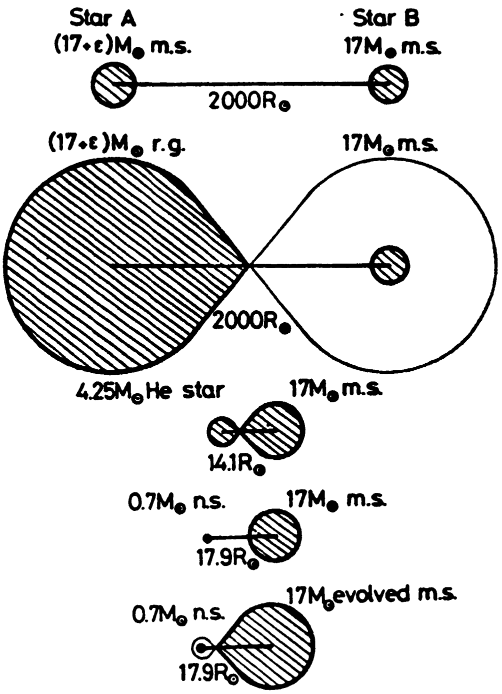

Fig.2. — A model of Cen X-3.

$a_1/a_0 = 0.0070$. Then Star A makes supernova explosion and a neutron star of mass $M_A = 0.7\ M_\odot$ is left as observed in Cen X-3. If the explosion is instantaneous and spherical, the orbit becomes elliptical with the eccentricity $e = 0.215$, and the separation becomes $a = (1-e)^{-1}a_1 = 1.27\ a_1 = 0.0089\ a_0$. If we assign $a = 17.9\ R_\odot$ for the present value of the separation corresponding to the orbital period of 2.087 days, we obtain the initial separation to have been $a_0 = 2000\ R_\odot$ for which the radius of the critical Roche lobe was $R_{cr,A0} = 760\ R_\odot$.

How large stellar radius did Star A reach in its course of evolution? The stellar luminosity should be fainter than the critical luminosity, which is $L_{cr} = 1.6 \times 10^5\ L_\odot$ for $M_{A1} = 4.25\ M_\odot$. If we assume the luminosity of a half of L_{cr} and the effective temperature of $T_{eff} = 3500$ K, we obtain the stellar radius to have been $R = 770\ R_\odot$. As this radius is not smaller than $R_{cr,A0}$, the star expanded large enough to initiate the mass transfer. In other words we reach a consistent model with some margin. For other Type I XCBS's the situation is essentially unaltered, i.e., we can construct consistent models: The mass of their optical component M_B is comparable with the mass escaping from the system $(M_{A0} - M_{A1}) \simeq M_B$ so that the exponential term in equation (2;SM) does not become excessively small.

4. ORIGIN OF TYPE II XCBS

For Type II XCBS, on the other hand, a serious difficulty arises if we imagine a scenario similar to those for Type I. It comes from the smallness of M_B, which results in an excessive closing up of the component star. Let us consider Her X-1 as a typical example, for which we take $M_B = 2.2\ M_\odot$ (Wheeler 1979). Because Star A is now a neutron star, its initial mass should have been more massive than the upper mass limit to the carbon deflagration supernova, for which we employ the lowest estimate of $M_{A0} = 5\ M_\odot$ (Wheeler 1978). The helium core mass for this star will be close to the Chandrasekhar limit so that we assume $M_{A1} = 1.5\ M_\odot$. Then we obtain $a_1/a_0 = 4.26 \times 10^{-4}$ by means of equation (2;SM) with $\ell = 1.7$. Because the mass of the neutron star is $1.3\ M_\odot$, we obtain further $a/a_1 = 1.06$. The observed orbital period of 1.70 days corresponds to $a = 9.11\ R_\odot$. Therefore the initial separation should have been as large as $a_0 = 2490\ a = 2.3 \times 10^4\ R_\odot$, which is too large to initiate the mass exchange. As seen from equation (2;SM), such results are common among the systems with $(M_{A0} - M_{A1}) > M_B$, i.e., among Type II XCBS's.

However, there exist such XCBS's in nature. How can we remove such difficulty? The fact that M_B is small indicates in itself that the mass exchange has been non-conservative. Therefore, only one possibility is to reduce the mean value of angular momentum which is carried away with unit mass of escaping matter. When Star A is a red giant, there may be a self-excited mass ejection, in which the envelope of Star A will be expelled by Star A itself as in the case of mass loss from a single star. In such case the gas particle has a velocity higher than the thermal speed when it leaves from the binary system. Therefore the effective value of ℓ will be appreciably smaller than 1.7. In the limiting case of high speed mass ejection, for example, only the angular momentum which was associated originally with the escaping gas, is carried away. It is about $\ell \simeq 0.25$ in the case of $M_A = M_B$, for example. Thus the result of the self-excited mass ejection will be the reduction of M_A and a gradual closing up of Star A to Star B. When the component stars close enough, the non-conservative mass exchange commences and the component stars become closer and closer according to equation (2;SM) with ℓ = 1.7. However, an excessive closing up will be avoided, if Star A has lost most of its hydrogen-rich envelope by the preceding self-excited mass ejection.

One may ask why such self-excited mass ejection does not take place in the precursor of Type I XCBS. In this connection it is interesting to note the following difference in stellar evolution. The stars more massive than 12 $M_\odot$ stay around yellow supergiant in and near the helium burning phase (see e.g., Lamb, Iben and Howard 1976). On the other hand the stars less massive than 12 $M_\odot$ evolve to red supergiant (see e.g., Barbaro, Chiosi and Nobili 1972), where appreciable self-excited mass ejection will take place. In the later phases of evolution the stars in both mass ranges become red supergiants but their lifetimes are too short to allow appreciable amount of mass ejection.

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DISCUSSION FOLLOWING SUGIMOTO AND MIYAJI

Shu: I would like to comment that the use of the Roche model becomes somewhat dubious when dealing with separations as large as a few thousand solar radii. The assumption of synchronism must almost certainly break down for such widely separated systems.

Sugimoto: The important parameter is not the geometry of the Roche model itself but the angular momentum carried away together with the gas outflowing from the system. The outflowing gas is, in any case, not in the synchronism. Such effects were taken into account when the particle trajectories were computed. For the size of the critical Roche lobe, the important thing is the size within which the gravitational pull from the companion can be neglected in determining stellar structure. In this sense such size is not so much different even when the synchronism breaks down.

Meyer-Hofmeister: The mass ratio is important for the question whether the mass transfer is conservative or not. For mass ratios far from 1 the thermal timescale of the secondary is much longer than the thermal timescale of the primary which forces loss of mass from the system.

Sugimoto: It depends not only on the mass ratio but also more critically on the evolutionary stages of the star, because the thermal timescale of the envelope depends strongly on the stellar radius. Therefore it depends on the initial separation between the components. When the mass exchange commences as in the cases late A, B, or C, it is well non-conservative, as has been shown in my first paper presented at this symposium.

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