ORIGIN OF VERY-SHORT ORBITAL-PERIOD BINARY SYSTEMS

Shigeki Miyaji
Department of Natural History, College of Arts and Sciences
Chiba University, Chiba 260, Japan

1. INTRODUCTION

Recent observations of four close binaries have established that there is a group of very-short orbital-period (VSOP) binaries whose orbital periods are less than 60 minutes. The VSOP binaries consist of both x-ray close binaries (4U1626-67; Middleditch et al. 1981 and 4U1916 -0.5; White and Swank 1982) and cataclysmic variables (AM CVn; Faulkner et al. 1972 and G61-29; Nather et al. 1981). Their orbital periods are too short to have a main-sequence companion. However, four binaries, none of them belongs to any globular cluster, are too abundant to be explained by capturing mechanism of a white dwarf. Therefore it seemed to be worth to present an evolutionary scenario from an original binary system which can be applied for all of VSOP binaries.

Evolutional scenarios of binary systems have been discussed by many authors (e.g. van den Heuvel 1981 and Tutukov 1981). However VSOP binaries can not be explained by their scenario. One reason is that scenarios so far proposed have treated only extream cases, e.g. mass conservative case and spiral-in case in the huge common envelope. So it is hard to explain highly compact but not coalesced system. The other reason is that the VSOP binaries consist of two evolved stars and their separations are less than one solar radius. (The companion of AM CVn should be a helium or carbon-oxygen white dwarf, and the case of G61 -29 may be a helium white dwarf; Nather et al. 1981.) Such system can not be formed by the first phase of mass transfer only, because 3 x 10^7 years (life of a neutron star progenitor; 8 $M_\odot$ star) is so short to make a slight change in abundances of companion star even if it is as heavy as a $0.7M_\odot$ star initially. We discuss detailed process of mass and angular momentum losses in section 2 and present a scenario of on the origin of VSOP binaries in section 3.

2. MASS AND ANGULAR MOMENTUM LOSS

Stable mass transfer including angular momentum loss by gravitational wave radiation was well studied by Paczyński and Sienkiewicz

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(1981) and Rappaport et al. (1981). They mimicked evolutions of cataclysmic variables (the case of main-sequence secondary) and showed that there is a minimum orbital period at (60-80) minutes. This minimum period is the results from the facts that mass transfer is driven by angular momentum loss by gravitational wave radiation and that structure of mass losing star becomes isentrope, i.e., Kelvin-Helmholtz timescale of mass losing star is longer than gravitational timescale. Stable mass loss from the system does not affect this situation because its timescale is Kelvin-Helmholtz timescale of mass losing star. In fact, Rappaport et al. (1982) computed models with slow mass loss and showed that there is not any significant difference from other results without mass loss. Moreover, as the companion star loses its mass, resultant degenerate star keeps its initial composition ratio. Therefore VSOP binaries should not be the products of stable mass transfer.

On the other hand, if mass transfer is rapid, well accepted spiral-in scenario poses a serious difficulty, i.e., the system should merge into a single star. However, when two components have similar mass, spiral-in episode is not correct because the mass in common envelope is also the same. Once angular momentum was transmitted to the envelope from the secondary, drag force does not work any more.

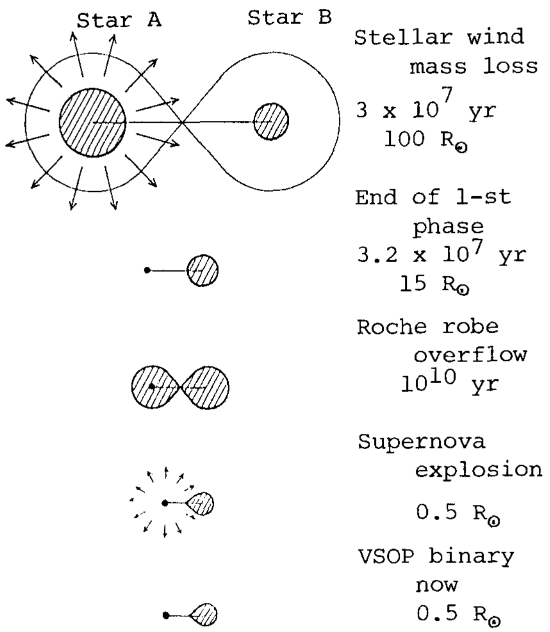
When the envelope overflows from the second Lagrangian point (L_2 point), angular momentum is lost by the acceleration of particles by the dipole gravitational potential of the binary. Following the trajectory of zero verocity particles, Nariai and Sugimoto (1977) showed that the particles takes away about 1.7 times of mean angular momentum if mass ratio $q \equiv M_A/(M_A+M_B) \gtrsim 0.05$. Therefore if common envelope overflows from L_2 point, the system begins to shrink unstably.

This acceleration mechanism, of course, works even for stable mass loss. However, stellar wind particle has, at least, escape velocity, so angular momentum loss is much smaller than the case of zero velocity particle. For the case of wind from a thin common envelope (which does not fill L_2 point), angular momentum loss is moderate because it starts from much shallower gravitational potential. We can not give exact timescale of shrinkage here but it is much longer than 10^{3-4} years (spiral-in timescale given by van den Heuvel 1981).

3. A SCENARIO OF VERY-SHORT ORBITAL-PERIOD BINARIES

Our scenario is illustrated in figure 1. As VSOP binaries contain x-ray close binaries, we choose $8M_\odot$ main-sequence star as initial primary (star A) and $1M_\odot$ secondary (star B). Initial separation of components is about $200R_\odot$.

After 3×10^7 years, star A begins to expand and fills up its Roche robe. Since OB star has lost large amount of its mass by stellar wind, the system shrinks a tenth of its initial separation. At 3.2×10^7 years, $1.3M_\odot$ O-Ne-Mg white dwarf and $1M_\odot$ main-sequence star are left and their separation is about $15R_\odot$.



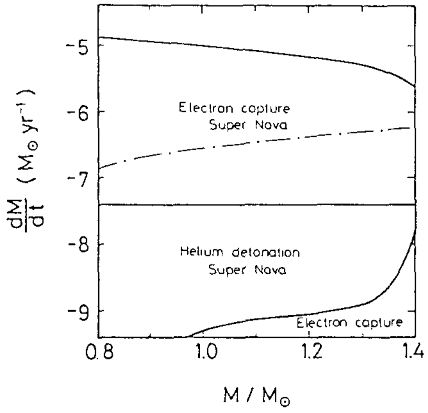


Fig. 2. Final Fate of Helium Accreting O-Ne-Mg White Dwarf.

Fig. 1 A Scenario of VSOP Binaries

After 10^{10} years, star B begins to expand and fills up its Roche robe. As 1$M_\odot$ star needs 10^{8} years to expands up to 100$R_\odot$, mass transfer rate from star B to star A is the order of 10^{-7} $M_\odot$/yr. If mass recieving star is a main-sequence star of 0.75$M_\odot$ and mass accretion rate is $\dot{M}$=2x10^{-7} $M_\odot$/yr, the radius of star B becomes only three times of its initial radius at 1.0$M_\odot$ (Neo et al. 1979). However, in this case, mass recieving star is a white dwarf so that it cannot accept all the amount of accreted mass. Because, on white dwarf, hydrogen burning releases about 10 times energy than that of gravitational energy release. From the figure 4 of Fujimoto (1982), $\dot{M}$=3x10^{-7} $M_\odot$/yr is enough large rate to form a stable hydrogen burning layer. If mass accretion rate is less than 2x10^{-7}$M_\odot$/yr, the white dwarf recurs weak shell-flashes. These shell-flashes do not grow into nova outburst but the envelope of white dwarf expands up to red giant size (Yasutomi et al. 1982). This red giant phase continues about a tenth of recurrence time of shell-flashes, e.g., about 10 years. Therefore, it is easy to fill up the Roche robe of white dwarf even at moderate Case B mass transfer. The rest of amount should overflow into a common envelope but its mass is smaller than that of white dwarf. Since angular momentum is lost by the wind from the common envelope, the system shrinks by the evolutional timescale of mass losing star; about 10^{7} years. This timescale is long enough to accumurated some amount of mass (~1$M_\odot$) onto a white dwarf.

Final fate of such white dwarf is studied by the model of helium accreting white dwarf (Nomoto et al. 1982), because mass accreting white dwarf grows in its mass by stable hydrogen burning or weak hydrogen shell-flashes. For the case of stable hydrogen burning, succeeding helium shell-flashes are weak and finally the white dwarf makes electron capture supernova explosion (figure 2). Then the common envelope is blown off so that a neutron star and a helium core are left finally. For the case of weak hydrogen shell-flashes ($\dot{M} \gtrsim 5\times10^{-8} M_\odot$/yr), helium shell-flash grows to a detonative burning and the white dwarf makes a supernova explosion as the case of helium accreting carbon-oxygen white dwarf (Nomoto 1980). In this case a white dwarf and a helium core are left behind.

This is a scenario on the origin of VSOP binaries. However, we here notice that this scenario is not the unique one. Because star A can be 4-8 $M_\odot$ main-sequence star and supernova explosion can be a carbon deflagration supernova. Although, in this case, x-ray binaries can not be explained because carbon deflagration supernova does not leave a neutron star.

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DISCUSSION FOLLOWING S. MIYAJI'S TALK

LAMB: I did not understand how the common envelope stage is reached after the white dwarf is formed. Could you explain that again?

MIYAJI: If the mass accretion is larger than a certain value, hydrogen is burning stably so that it forms something like a red giant's envelope, so that transferred mass cannot accumulate anymore, because it has say, 1 $R_{\odot}$ or 10 $R_{\odot}$. The Roche lobe is filled by such a red-giant-like envelope and then the rest of the transferred mass should form a common envelope.

MEYER: The common envelope, which you would like to blow away by the supernova explosion, is that a very low density envelope or an ordinary red giant type envelope?

MIYAJI: I think it is a red giant gype envelope.

MEYER: The reason I ask is that the computations that we did indicate that the spiralling-in times are very short. The reason for that is, that basically you create from this friction of the spiralling-in, a luminosity of the order of the Eddington luminosity and that gives you timescales (for orbital periods of a few hours or fractions of an hour), of the order of only 1000 years, and I doubt whether a supernova explosion would occur on such a short timescale just at the right moment. So might this create a problem for that part of your scenario?

MIYAJI: Yes. But we have to form a common envelope, so it needs a mass accretion rate larger than 10^{-7} $M_{\odot}$/yr and the main sequence star also has to evolve to become large, so that its timescale is of the order of 10^{8} years, this gives you 10 $M_{\odot}$ or so. Of course, the spiralling-in timescale is very short, but after the spiralling the white dwarf becomes very close to 1.4 $M_{\odot}$ or so, so there may be a possibility.

FINZI: I wanted to ask why do you need to create a common envelope before the supernova explosion, isn't it enough that you have an inflow of mass onto a white dwarf that is close to the Chandrasekhar limit.

MIYAJI: Because we need to have some rapid mass and angular momentum loss process. However, once such a rapid angular momentum loss works, the main problem is how to halt the coalescence.