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Evolution of Millisecond Binary Pulsars with Short Orbital Periods

Abstract

We discuss a white dwarf mass versus orbital period relation for binary millisecond pulsars with short orbital periods (less than 20 days). Due to effects of angular momentum losses the $P_{\rm orb}$-$M_{\rm WD}$ relation is more complex than relations based on "conservative" binary evolution so far used in literature. Effects of angular momentum losses (possibly in combination with the absence of a unique core mass-radius relation for star $M_{\rm He} < 0.15$ M$_\odot$) leads to systematically larger $M_{\rm WD}$ at the same final binary period.

I Introduction

The evolutionary history of low-mass X-ray binaries (LMXB) which leads to a binary millisecond pulsar system (BMSP) depends on two main timescales: 1) hydrogen burning timescale $t_{\rm nuc}$, 2) angular momentum loss timescale $t_{\rm am}$. The latter includes angular momentum losses by magnetic braking and by mass loss from the system. For systems with initial orbital periods longer than 10 days, $t_{\rm nuc}$ is much shorter than $t_{\rm am}$ and the angular momentum losses by magnetic braking can be neglected. In this case the relation between final orbital period and $M_{\rm WD}$ may be described by rather simple approximation formula (see latest revised form in Rappaport et al. 1995).

However if $t_{\rm nuc} \simeq t_{\rm am}$ the angular momentum losses begin to play a crucial role. If the initial periods are near the so called bifurcation point (Tutukov et al. 1985; Pylyser & Savonije 1988) then the binary evolution may become quite complicated. Small changes in the initial period (P_i) may lead to three possibilities for the final periods (P_f): 1) $P_f < P_i$, 2) $P_f \simeq P_i$, 3) $P_f > P_i$. Here I should like to show how the effects of the angular momentum losses in combination with making a full binary evolutionary calculations modify the relation between $M_{\rm WD}$-$P_{\rm orb}$ (final).

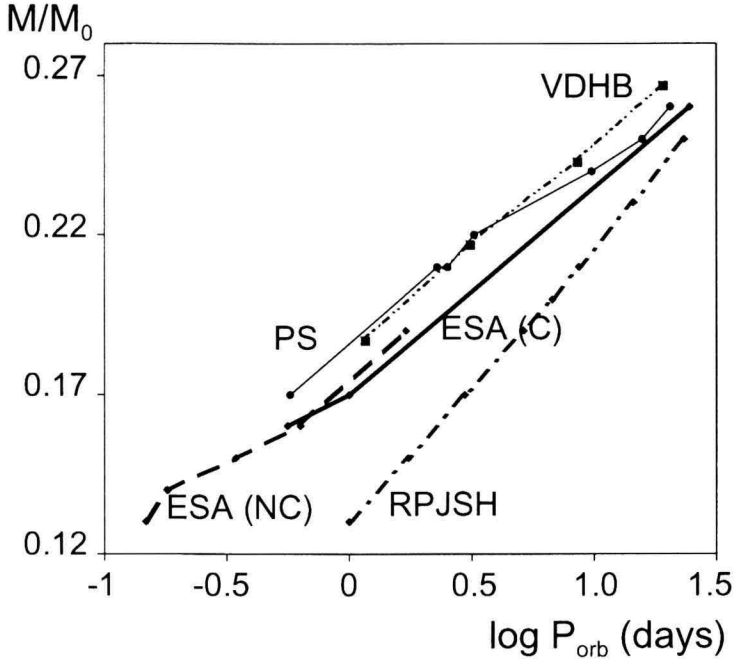

Figure 1. The relation between final $M_{\rm WD}$ and $P_{\rm orb}$. Thick line, c models (ESA); dot line, $n-c$ models (ESA). $n-c$ case where besides the orbital angular momentum loss by magnetic braking, mass and angular momentum losses from the system have been taken into account. c case where only orbital angular momentum loss by magnetic braking has been used. Dash-dot-dot line, van den Heuvel & Bitzaraki (1994) models; thin line, Pylyser & Savonije (1988) models; and dash-dot line, semi-empirical relation RPJSH.

II Evolutionary calculations

To investigate the binary evolution when $t_{\rm nuc} \simeq t_{\rm am}$ it is necessary to use full binary evolutionary computations which include both the nuclear evolution of the secondary as well as the orbital evolution of the binary. In our analysis we have used for the following combinations of donor mass and accretor mass ($M_d/{\rm M}_\odot, M_{acc}/{\rm M}_\odot$): Pylyser & Savonije (1988) (1,1) (1.5,1) $Z = 0.02$; van den Heuvel & Bitzaraki (1994) (1,1.4) $Z = 0.02$; Ergma, Sarna & Antipova (1996; hereafter ESA) (1,1.4) $Z = 0.03$; results of the ESA calculations have been obtained using the program described by Muslimov & Sarna (1993), and Sarna & De Greve (1994) has been used.

In Figure 1 we have drawn the $M_{\rm WD}$-$P_{\rm orb}$ dependence obtained in various calculations where $M_{\rm WD}$ is the mass of the remaining white dwarf core of the donor star. Also we have used the period-mass relation obtained by Rappaport et al. (1995; hereafter RPJSH)

$$P_{\rm orb} \approx 0.374[R_0 M_{\rm WD}^{4.5}/(1+4M_{\rm WD}^4)+0.5]^{1.5} \cdot M_{\rm WD}^{-0.5}$$

where $M_{\rm WD}$ is in solar units, $P_{\rm orb}$ is in days, and the quantity in square brackets is expressed in units of solar radii ($R_0 = 4850$ R$_\odot$).

From this figure the influence of making a full evolutionary calculations, including the angular momentum losses is clearly seen. If we compare the $M_{\rm WD}$-$P_{\rm orb}$ dependence resulting from full binary evolution calculations with realistic angular momentum losses with those computed using the above semi-empirical relation then we see that this relation gives systematically lower white dwarf mass values, the differences increasing from ~ 0.02 M$_\odot$ at $P_{\rm orb} \sim 20$ days, to more than 0.05 M$_\odot$ for $P_{\rm orb} \sim 1.5$ day. Futhermore, for a fixed white dwarf mass the estimated orbital period value is much longer ($\Delta \log P_{\rm orb}$(days) $\approx$ ranges from 0.7 to 0.4). One clearly notices the convergence of all tracks when the orbital period increases.

III Discussion

As to the reasons for the systematically enlarged core masses at the same final orbital periods, which result from the full evolutionary, we can think of two possibilities (or a combination of these): 1) as pointed out by Rappaport et al. (1995) for stars with small helium core mass ($\leq 0.15 - 0.2$ M$_\odot$) there probably is no longer a unique core-mass radius relation, i.e. the value of the outer radius will also depend on the mass of the hydrogen-rich envelope. Using full evolutionary computations such an effect will automatically be taken into account and will yield a systematic difference relative to the outcomes in which a unique core-mass. 2) The fact that for short initial orbital periods and low donor masses, the mass transfer may cause the donor to no longer be completely in thermal equilibrium as the mass transfer timescale differs by less than an order of magnitude from the thermal timescale of the donor. In this case the radius of the donor will no longer be its thermal equilibrium radius, such that a standard core-mass radius relation does not longer apply.

IV Conclusion

It was shown that for BMSP with orbital period less than 20 days, the relation between $M_{\rm WD}$ and $P_{\rm orb}$ is more complicated than relation based on "conservative" binary evolution so far used in literature. Due to the effects of angular momentum losses the orbital periods increase less during the evolution, which, possibly in combination with the other effects mentioned in section 3, leads to systematically longer white dwarf masses at the same final binary period. At the shortest orbital periods (near one day) the difference may be as large as over 30%. For orbital period longer than 20 days the difference becomes negligible.

References

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