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BINARIES WITH COMPACT COMPONENTS: THEORETICAL AND OBSERVATIONAL CHALLENGES

Ph. Podsiadlowski,[1] S. Rappaport,[3] and E. Pfahl[2]

RESUMEN

Presentamos una revisión sobre el reciente progreso teórico realizado en nuestra comprensión de binarias de rayos X, promovido en su mayoría, por nuevas observaciones y que ilustra la acción recíproca entre teoría y observaciones, considerando como ejemplos binarias de rayos X de masa intermedia, evolución impulsada por irradiación, fuentes de rayos X ultraluminosas y estrellas de neutrones con impulsos de baja velocidad.

ABSTRACT

We report on recent progress in our theoretical understanding of X-ray binaries, which has largely been driven by new observations, and illustrate the interplay between theory and observations considering as examples intermediate-mass X-ray binaries, irradiation-driven evolution, ultraluminous X-ray sources and neutron stars with low-velocity kicks.

Key Words: **BINARIES: CLOSE — BLACK HOLE PHYSICS — STARS: NEUTRON — X-RAYS: STARS**

1. INTRODUCTION

Our general understanding of binaries with compact components, in particular those containing neutron stars and black holes still has serious gaps, and theoretical progress is often driven by new observational discoveries. Observations not only help to guide theorists, but also provide important constraints that a successful theory has to satisfy. In this contribution, we discuss the interplay between theory and observations using several selected topics, including both neutron-star and black-hole binaries.

2. THE IMPORTANCE OF INTERMEDIATE-MASS X-RAY BINARIES

One of the major recent developments in the field of X-ray binary research has been the realization that X-ray binaries with intermediate-mass companion stars (IMXBs) are much more important than believed previously. Indeed, IMXBs provide a particularly good example that illustrate the interplay between theory and observations. The *observations* by Casares et al. (1998) showed that the companion of the X-ray binary Cygnus X-2, formerly classified as a low-mass X-ray binary (LMXB), was far too luminous and far too hot to be consistent with a sub-giant in a 10-d orbit. The *theoretical* resolution of this surprising observation (King & Ritter 1999; Podsiadlowski & Rappaport 2000) was that the system must have originated from an IMXB rather than an LMXB, where the mass of the companion star must originally have been around $3.5\,M_\odot$ (also see Tauris et al. 2000; Kolb et al. 2000). However, this implies that the system must have survived as a binary despite an extremely high mass-transfer rate ($\sim 10^{-5}\,M_\odot\,\mathrm{yr}^{-1}$) – several orders of magnitude above the Eddington accretion rate – ejecting most of the transferred mass. How can a system eject all of this mass? Again, *observations* may provide the essential clues. Radio observations of the relativistic jet system SS 433 (Blundell et al. 2001) and possibly of Cygnus X-3 (Miller-Jones et al. 2004, in preparation) show that most of the transferred mass in these systems is lost in an equatorial, disk-like outflow.

Podsiadlowski, Rappaport & Pfahl (2002) and Pfahl, Rappaport & Podsiadlowski (2003) have systematically investigated *theoretically* the role of IMXBs and found, not surprisingly, that IMXBs are much easier to form than traditional LMXBs, since these systems can more easily survive as binaries both a common-envelope phase and the supernova in which the neutron star is formed. After the initial high mass-transfer phase, IMXBs are almost indistinguishable from LMXBs; but since they have much higher birthrates, Pfahl et al. (2003) predict that 80 – 95 % of all L/IMXBs in fact originate from IMXBs.

How can *observations* help to confirm this prediction? Pfahl et al. (2002a) proposed that the thousands of weak X-ray sources in the Galactic center

[1] Dep. of Astrophysics, University of Oxford, Oxford, OX1 3RH, UK.
[2] Center for Astrophysics, Cambridge, MA 02138, USA.
[3] Center for Space Research, M.I.T., Cambridge, MA 02139, USA.

region, discovered in large numbers with *Chandra* (Wang et al. 2002) are in fact the progenitors of IMXBs and HMXBs, where a neutron star accretes matter from the wind of an intermediate-mass companion before the latter fills its Roche lobe (for alternative suggestions, see Willems & Kolb 2003; Belczynski & Taam 2003). Bandyopadhyay et al. (2004) have obtained VLT observations to look for infrared counterparts of some 70 of these weak sources. These observations may already provide an important test of this prediction.

Another *observational* test to distinguish between LMXBs and IMXBs is to look for chemical anomalies. Many of the descendants of IMXBs should be helium-rich and show evidence for CNO-processing. Such anomalies may manifest themselves directly spectroscopically or indirectly through their effects on X-ray bursts (Cumming 2003).

3. PROBLEMS WITH THE STANDARD MODEL AND IRRADIATION-DRIVEN EVOLUTION

Pfahl et al. (2003) performed the first binary population synthesis study of L/IMXBs using realistic binary evolution models. One of their main conclusions was that the standard model for L/IMXBs failed to reproduce some of the main features of the observed population. The two most significant failures are: (1) the overproduction of L/IMXBs by a factor of $10-100$ (though consistent with the birthrate of binary millisecond pulsars), and (2) the luminosity distribution, where the theoretical distribution neither produces enough luminous L/IMXBs (with $L_{\rm X} > 10^{37}\,{\rm ergs\,s^{-1}}$) nor reproduces the observed correlation between X-ray luminosity and orbital period (Podsiadlowski et al. 2002).

One major omission in the standard model is that it does not take into account the strong X-ray irradiation of the secondary which can fundamentally change the evolution of the system by either driving a wind from the secondary (Ruderman et al. 1989) or by driving expansion of the secondary (Podsiadlowski 1991). Even a modest expansion of the secondary ($\sim 10\,\%$) can drive mass-transfer cycles (Hameury et al. 1993) where the mass-transfer rate $\dot{M}$ is larger than the rate without irradiation effects by a factor $\gtrsim 10$, which at the same time shortens the X-ray active lifetime by a proportionate amount. Pfahl et al. (2003) demonstrated that the inclusion of such mass-transfer cycles could potentially solve both of the major problems mentioned above, by increasing the typical observed X-ray luminosity by a factor of 10 or more and at the same time eliminating the L/IMXB overproduction problem, but still producing enough binary millisecond pulsars.

At the present time, the effects of irradiation on the secondary are still very poorly understood. Phillips & Podsiadlowski (2002) have shown that the external irradiation can dramatically distort the shape of the companion which has important implications for modelling ellipsoidal lightcurves and determining radial-velocity curves of the secondary. One of the key uncertainties is how much energy is transported from the irradiated side to the back side by irradiation-driven circulation. Even the transport of only $1\,\%$ of the intercepted irradiation energy can have drastic effects on the appearance and the further evolution of the secondary. To help answer these questions, Beer has developed a custom-designed 3-d stellar hydrodynamics code to study the irradiation-induced circulation (initially using a polytropic equation of state, which is now being extended to include a thermodynamic equation; Beer & Podsiadlowski 2002a,b). Some of his preliminary results show that the circulation velocities are a significant fraction of the sound speed and that a substantial amount of energy is transported to the backside in the form of kinetic energy (rather than thermal energy) where it is thermalized and raises the temperature by more than 1000 K in the case of an LMXB companion.

Again, observations will play in essential role in constraining the theoretical models (in particular the turbulent viscosity in the outer shear layer). These constraints may involve ellipsoidal light curves, phase-dependent spectral variations and distortions of radial-velocity curves. Indeed many of these effects have already been observed in a number of systems (e.g. HZ Her/Her X-1, Cyg X-2, Nova Sco, AA Dor).

4. ULTRALUMINOUS X-RAY BINARIES

Ultraluminous X-ray sources (ULXs) are luminous X-ray sources outside the nuclei of external galaxies, typically defined to have an X-ray luminosity larger than $10^{39}\,{\rm ergs\,s^{-1}}$. They were originally discovered by *Einstein* (Fabbiano 1989) and have been found in large numbers by *ROSAT* and most recently *Chandra*. While it had been suggested (e.g. Colbert & Mushotzky 1999) that these may contain intermediate-mass black holes of $10^2-10^4\,M_\odot$, it now seems more likely that at least the majority form the luminous tail of the stellar-mass black-hole binary distribution (e.g. King et al. 2001, 2004).

Podsiadlowski, Rappaport & Han (2003) performed a systematic study of the formation and the evolution of black-hole binaries using realistic binary evolution calculations and found that indeed their models were consistent with the observed luminosity function and the typical number in a galaxy (of

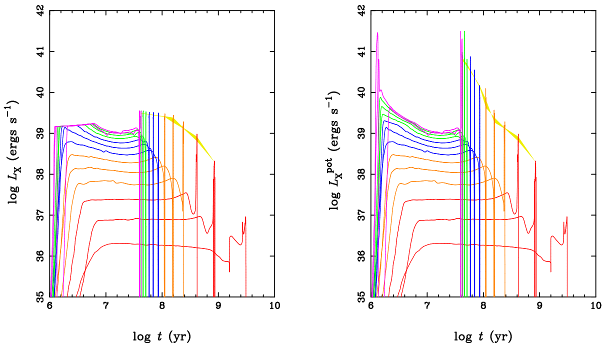

Fig. 1. X-ray luminosity, assuming Eddington-limited accretion, (left) and *potential* X-ray luminosity, assuming non-Eddington limited accretion, (right) for binary sequences containing a black hole with an initial mass of $10\,M_\odot$ and initially unevolved secondaries from 2 to $17\,M_\odot$ (roughly right to left; bottom to top). (From Podsiadlowski et al. 2003)

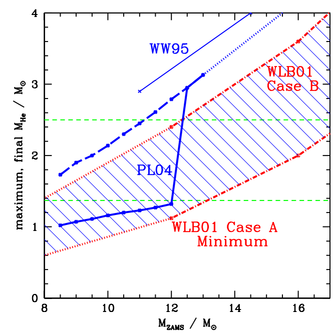

Fig. 2. Final mass (thick solid line) and maximum mass (thick dashed line) of the helium core in single stars as a function of initial mass according to Poelarends & Langer (2004, PL04), extrapolated for initial masses above $12.5\,M_\odot$ (the final helium core masses from the calculations of Woosley & Weaver [1995] are indicated by a thin solid line). The hatched region shows the final helium core masses expected in close binaries (from the calculations of Wellstein et al. 2001 [WLB01]). The light dashed horizontal lines give the range for the final helium core mass for which the star may experience an electron-capture supernova. Note that the parameter range for which this may occur for a single star is very small.

order one to a few). Figure 1 shows the X-ray luminosity (left) and potential X-ray luminosity (right) as a function of time for a sequence of binary models. The potential X-ray luminosity is the luminosity of a system assuming that accretion is not Eddington limited and that all the mass transferred from the companion can be accreted, radiating at the appropriate accretion efficiency. As the right panel shows, many of the more massive systems have two phases in which the potential X-ray luminosities are in excess of $10^{39}\,\mathrm{ergs\,s^{-1}}$, where these systems might appear as ULXs; in an initial phase where mass-transfer occurs on a thermal timescale and a later phase when the secondary evolves up the giant branch, where the evolution is driven by hydrogen shell-burning. Note, in particular, that the systems spend substantially more time in the shell-burning phase than in the initial thermal timescale phase. Indeed, GRS 1915+105, which is the only known Galactic ULX, is well explained by these models.

In order for these systems to be ULXs requires a luminosity in excess of the Eddington limit, typically by a factor of a few and less than a factor 20 for even the most luminous systems, where this requirement is further reduced if moderate geometrical beaming (King et al. 2001) is important. We note that super-Eddington luminosities are commonly observed in a number of neutron-star X-ray binaries, presumably because the accretion flow is funnelled towards the poles of the neutron star by magnetic fields. While this mechanism is not applicable to black-hole binaries, Begelman (2002) has argued that such super-Eddington luminosities can be explained in radiation-pressure dominated, magnetic disks.

5. A DICHOTOMOUS KICK-SCENARIO FOR NEUTRON-STAR KICKS

It has long been established that neutron stars receive a kick with a median velocity larger than $200\,\mathrm{km\,s^{-1}}$. Since such a velocity is a factor of 5 to 10 larger than the central escape velocity of even a massive globular cluster (GC), this implies that most neutron stars forming from single stars should be ejected from clusters. On the other hand, rich GCs contain as many as ~ 1000 neutron stars (i.e. $10-20\,\%$ of the neutron stars formed). This problem is known as the *neutron-star retention problem* (for a detailed review see Pfahl et al. 2002b).

The retention problem is dramatically reduced if most neutron stars are born in massive binaries, since in this case the momentum imparted to the neutron star is shared with a companion star, leading to much lower systemic velocities and making it much easier to retain the system (Brandt & Podsiadlowski 1995). As Pfahl et al. (2002b) have shown this effect dramatically increases the number of neutron stars that can be retained, although it may not be sufficient to explain the observed numbers, unless globular clusters were initially much more massive (Drukier 1996). The problem can be substantially reduced if a significant fraction of neutron stars only receive a small kick (Pfahl et al. 2002b). Indeed, there is strong evidence that some neutron stars must receive rather small kicks at birth from a newly established class of high-mass X-ray binaries, which are relatively wide but have very low eccentricities (Pfahl et al. 2002c). The prototype system is X Per with an orbital period of 250 d and an eccentricity of ~ 0.10. Since the system is too wide for tidal effects to be important, this requires that the neutron star can only have received a moderate natal kick. Pfahl et al. (2002c) and Podsiadlowski et al. (2004) speculated that whether a neutron star receives a large or a small kick depends on whether the progenitor was single or a member of a close binary, where it lost its envelope soon after the main-sequence phase (i.e. in case B mass transfer). As is not widely known, the evolution of the core of a massive star and its final pre-supernova structure differs substantially between single stars and stars in close binaries. Massive stars that lose their envelopes in case B mass transfer develop much smaller helium cores and ultimately smaller iron cores (see Brown et al. 1999). Moreover, as the most up-to-date stellar evolution calculations have shown (see Podsiadlowski et al. 2004), massive stars in the range of $8-11\,M_{\odot}$ that have lost their hydrogen-rich envelopes before ascending the asymptotic giant branch do not experience a second dredge-up phase, which would dramatically reduce the mass of the helium core (see Fig. 2). This suggests that single stars in this mass range most likely end their evolution as ONeMg white dwarfs rather than in a supernova, while stars that have lost their envelopes can explode in a supernova, most likely an electron-capture supernova. Podsiadlowski et al. (2004) speculated that the core collapse in a small iron core or an electron-capture supernova leads to a fast (prompt) explosion where the instabilities that produce large kicks in more massive cores do not have time to grow. This suggests a dichotomous scenario for neutron-star kicks, where stars in close binaries, producing small pre-supernova cores, lead to fast (prompt) supernova explosions with low kicks, while stars with more massive cores lead to slow explosions with a standard high kick. Indeed this scenario has recently received strong, theoretical support from the core-collapse calculations by Scheck et al. (2004), which show that the collapse of a small core produces a fast explosion with a small kick, while the collapse of a massive core leads to a slow explosion where convection-driven instabilities have time to grow and produce large supernova kicks (but also see Fryer & Warren 2004).

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