Aspherical supernova explosions and formation of compact black hole low-mass X-ray binaries

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ABSTRACT

It has been suggested that black hole low-mass X-ray binaries (BHLMXBs) with short orbital periods may have evolved from BH binaries with an intermediate-mass secondary, but the donor star seems to always have higher effective temperatures than measured in BHLMXBs. Here we suggest that the secondary star is originally an intermediate-mass (∼2–5 M⊙) star, which loses a large fraction of its mass due to the ejecta impact during the aspherical supernova explosion that produced the BH. The resulted secondary star could be of low mass (∼1 M⊙). Magnetic braking would shrink the binary orbit and drive mass transfer between the donor and the BH, producing a compact BHLMXB.

Key words: binaries: close – supernovae: general – X-rays: binaries.

1 INTRODUCTION

There currently exist approximately 20 stellar-mass black hole (BH) candidates in binary systems (Casares 2006; Remillard & McClintock 2006). Nine of these systems are defined as compact BH low-mass X-ray binaries (LMXBs) with short orbital periods (∼≤1 d) and donors of mass ∼≤1 M⊙ (Lee, Brown & Wijers 2002; Ritter & Kolb 2003; Podsiadlowski, Rappaport & Han 2003). The short orbital periods of these BHLMXBs imply that they must have undergone secular orbital angular momentum loss, as mass transfer from the less massive donor star to the more massive BH always causes the orbit to widen. The standard formation scenario, in which the progenitor systems initially contain a massive primary and a low-mass secondary, faces several difficulties, as summarized in Justham, Rappaport & Podsiadlowski (2006) and Ivanova (2006) and noted here. (i) The progenitor binaries with extreme mass ratios (>20) are very difficult to form, considering the fact that massive stars tend to have binary companions with similar masses (Pinsonneault & Stanek 2006); (ii) the secondary star, because of its low mass, may not have enough energy to eject the envelope of the BH progenitor during the common envelope evolution phase, unless a significant fraction of the envelope has been previously lost through a very efficient stellar wind; and (iii) the binary is likely to be disrupted during the supernova (SN) explosion that produced the BH.

There have been quite a few alternative scenarios suggested for the formation of compact BHLMXBs. Eggleton & Verbunt (1986) suggested that the progenitor of a BHLMXB is a triple star in which a massive close binary is accompanied by a late-dwarf. After the evolution of the close binary into an ordinary X-ray binary, the compact object is engulfed by its expanding massive companion, and spirals in to settle at its centre. The resulting Thorne–Zytkow object (TZO) gradually expands until it attains the size of the late-dwarf orbit. Then a second spiral-in phase ensues, leading to the formation of a low-mass close binary. However, it is difficult for this scenario to explain the spatial distribution and space velocities of LMXBs. Podsiadlowski, Cannon & Rees (1995) proposed that during the evolution of TZO the central neutron star (NS) may be converted into a BH by accretion, and part of the envelope may collapse into a massive disc, which may become gravitationally unstable and lead to formation of low-mass stars or planets. The efficiency of NS accretion in this case is, however, highly uncertain. Ivanova (2006) suggested that a subset of short-period BHLMXBs could be powered by mass transfer from pre-main-sequence donors, although they suffer from the short lifetime problem (∼10⁷ yr). Podsiadlowski et al. (2003) and Justham et al. (2006) assumed that the secondary star is initially an intermediate-mass star, which is more likely to survive the common envelope evolution to form an intermediate-mass X-ray binary (IMXB). Along with mass transfer between the secondary and the BH, the secondary’s mass decreases to become ∼≤1 M⊙, and the binary becomes an LMXB with long lifetime (∼10⁹–10¹⁰ yr). To maintain long-term orbital shrinkage, the donor stars are further assumed to be Ap and Bp stars so that magnetic braking can work (alternatively, a circumbinary disc could do the same job without requiring the secondary stars to possess anomalously high magnetic fields, see Chen & Li 2006). However, the calculated effective temperatures of the donor stars are not compatible with the observed values which indicate that the donor masses should be ∼≤1 M⊙, at least at the onset of mass transfer.

Now the situation is that the formation processes require that the secondary is likely to be an intermediate-mass star, while apparent donor spectral classes suggest the donor star would be of low mass all the way. A plausible solution to this puzzle is that the secondary...
is initially an intermediate-mass star, but loses a significant part of its mass after the formation of the BH. In this work we explore the possibility of mass loss from the secondary by the impact from the aspherical SN ejecta.

2 MASS LOSS DUE TO SN IMPACT

BH formation may be associated with a SN explosion. In the framework of current stellar evolution theories, stars more massive than \(~\sim 40\, M_\odot\) collapse to BHs directly with no SN explosions. If the initial stellar mass is between \(~\sim 20\) and \(~\sim 40\, M_\odot\), a BH forms in a two-stage process, where the collapse first leads to the formation of a NS accompanied by a SN, which is subsequently converted into a BH through accretion from the SN fallback (e.g. Fryer 1999).

Observationally, Israeli et al. (1999) and González Hernández, Rebolo & Israeli (2007) have presented favorable evidence that the BH in the LMXB Nova Sco 1994 (GRO J1655–40) formed in a SN event. From high-resolution spectra, they found that the atmosphere of the companion was enriched by a factor of \(~\sim 6–10\) in several \(\alpha\)-process elements (O, Mg, Si and S), indicating that the compact primary most likely formed in a SN event of a massive star whose nucleosynthetic products polluted the secondary, as some of these elements cannot have been produced in a low-mass secondary (see however Foellmi, Dall & Depagne 2007, for negative argument). González Hernández et al. (2006) also found supersolar abundances of Mg, Al, Ca, Fe and Ni in the atmosphere of the companion star in the BHLMXB XTE J1118+480, and reached the similar conclusion. Additional independent evidence that the BH was formed in a SN explosion comes from the peculiar velocities measured for GRO J1655–40 (Mirabel et al. 2002) and XTE J1118+480 (Gualandris et al. 2005).

The SN explosion can influence the companion’s structure through hydrodynamic impact. The impact of the SN ejecta on a nearby companion may be quite dramatic. The supernova ejecta may either directly strip material from the companion by direct transfer of momentum or, evaporate the envelope through the conversion of the blast kinetic energy into internal heat (McCutskey & Kondo 1971; Suntany 1974a,b; Cheng 1974). Wheeler, Lecar & McKee (1975) analytically estimated the amount of mass lost from the companion as a result of the inelastic collision and the shock heating. They found that, in the case of spherical SN explosions, the fraction of lost mass from the companion depends on the value of the parameter \(\Psi\), which is defined as

\[
\Psi = \frac{1}{4} \frac{M_{SN}}{M_c} \frac{R^2}{a_0^2} \left( \frac{v_{SN}}{v_{es}} - 1 \right),
\]

where \(M_{SN}\) is the mass of the SN ejecta, \(M_c\) the mass of the companion, \(R\) the radius of the companion, \(a_0\) orbital separation just before the SN, \(v_{SN}\) the ejecta velocity, and \(v_{es}\) the escape velocity from the companion, respectively. Note that \(v_{es}\) is weakly dependent on the position within the regions to be stripped and ablated. It would be increased by about a factor of \(\approx 2\) at the bottom of the envelope. For an \(n = 3\) polytrope, which is appropriate for an unevolved star, half of the stellar mass is ejected when \(\Psi \sim 2\), and the star is completely destroyed when \(\Psi \sim 10\). Numerical simulations were performed for supernova impacts on both low-mass main-sequence companions (Fryxell & Arnett 1981; Taam & Fryxell 1984) and low-mass red giants (Livne, Tuchman & Wheeler 1992). The most recent high-resolution hydrodynamic simulations made by Marietta, Burrows & Fryxell (2000) show that the analytic estimates by Wheeler et al. (1975) do provide ballpark estimates of the ejected mass for the main-sequence star case when \(\Psi < 1\).

However, the high degree of polarization measured in several SNe (e.g. Wang et al. 2001; Leonard et al. 2002; Leonard & Filippenko 2005) strongly suggests that perhaps most SN explosions are aspherical. SNe associated with gamma-ray bursts (GRBs) are obviously aspherical, as GRBs are generally believed to be highly asymmetric phenomena (Woosley & Bloom 2006). The light curve and the nebular line features of GRB-SN 1998bw were found to be in conflict with what is expected from a spherically symmetric explosion model (Mazzali et al. 2001). Maeda et al. (2002) showed that this configuration can be obtained in an axisymmetric explosion. In such an explosion, Fe is mostly ejected at high velocity in a jet along the polar direction, while nearer the equatorial plane relatively low-velocity O is mostly ejected. It is now widely believed that these most energetic SNe, described as ‘hypernovae’, are bipolar explosions. Assuming that the secondary is impacted by jet-like SN debris with a solid angle \(\Omega\), equation (1) can be then modified to be

\[
\Psi = \frac{\eta \, M_{SN}}{4 \, M_c} \frac{R^2}{a_0^2} \left( \frac{v_{SN}}{v_{es}} - 1 \right),
\]

where \(\eta = 4\pi/d\). Note that \(M_{SN}\) and \(v_{SN}\) here correspond to the jet-like component in the SN ejecta. All hypernova models show that the jet emerges along the rotation axis of the compact object (e.g. Burrows et al. 2007, and references therein), which is implicitly assumed to be perpendicular to the orbital plane if in binary systems. However, anisotropic SN explosion can lead to misalignment between the spin and orbital axes. In at least two BH binaries, GRO J1655−40 and SAX J1819−2525, the observed relativistic jets appear not to be perpendicular to the orbital plane (Maccarone 2002, and references therein). If the jet directions are indicative of the direction of the spin of the BH, then the most likely explanation is that the misalignment occurred during the formation process of the BH, and that subsequent evolution has not had time to bring about alignment (King et al. 2005).

According to the calculations by Maeda et al. (2002) and Maeda (2006) for SN 1998bw, the opening angle of the ejecta in the polar direction is around \(30^\circ\). If we adopt a more conservative value of \(45^\circ\), \(~\sim 0.3\pi\). Fits to the observational data suggest that the velocity of the ejecta in SN 1998bw can be high as a few \(10^4\) km s\(^{-1}\). For a \(4-M_\odot\) main-sequence secondary in 1-d orbit, inserting typical values for the parameters in the above equation, we have

\[
\Psi \simeq 2.5 \left( \frac{\eta}{10} \right) \left( \frac{M_{SN}/4\, M_\odot}{M_c/4\, M_\odot} \right)^2 \left( \frac{(R/3\, R_\odot)}{(a_0/10\, R_\odot)} \right)^2 \left( \frac{v_{SN}/10^4\, km\, s^{-1}}{v_{es}/800\, km\, s^{-1}} \right)^{-1},
\]

suggesting that a large fraction of the stellar mass could be lost. Note that mass ejection is efficient for narrow systems. This is in accordance with the fact that the post-explosion binary has to be close enough to start the mass transfer driven by orbital angular momentum loss. Population synthesis calculations show that BHXBs with intermediate-mass (\(~\sim 2–5\, M_\odot\)) secondaries are born with orbital periods in the range from \(~\sim 0.5\) to \(~\sim 5\, d\) (Podsiadlowski et al. 2003). Finally we emphasize that the above estimate is just of the order of magnitude, and may have substantial errors due to the uncertainties in the morphology of hypernova explosions and the interaction of the SN ejecta with the secondary, especially in the case of \(\Psi \gtrsim 1\). These issues could only be resolved by future high-resolution numerical simulations of aspherical SN–secondary interactions. However, equation (3) does suggest that we need to seriously consider the possibility of efficient mass loss from the secondary by SN impact.
According to the calculations by Marietta et al. (2000), immediately after the impact the secondary star is puffed up, much like a pre-main-sequence star. Because the remaining envelope is out of thermal equilibrium, the luminosity of the remnant will vary dramatically with a Kelvin–Helmholtz time-scale $\sim 10^3–10^4$ yr. After thermal equilibrium is reestablished, the remnant will return to the main sequence along a Kelvin–Helmholtz track and then will continue its evolution at a rate prescribed by its new mass. If the stellar mass is now $\lesssim 1\, M_\odot$ and the orbital period $\sim 1\, d$, magnetic braking will cause the orbit to shrink, and drive mass transfer on to the BH, leading to the formation of a compact BHLMXBs.

### 3 DISCUSSION

In this work we argue that BHLMXBs may begin with an intermediate-mass secondary, and that there could be rapid mass loss at the birth of the BH accompanied by a SN explosion. In the case of highly aspherical SN explosions, the ejecta impact could strip and blow the majority of the secondary’s mass, leaving it as a low-mass star. If the orbit is close enough, with the help of magnetic braking, the binary will evolve to a short-period LMXB. The low-mass donor also makes it possible to account for the observed cool spectral types. If the secondary loses little mass during the SN explosion, an IMXB will form, which will ultimately evolve to be a wide LMXB. Note that the efficient mass loss requires high asphericity of the SN explosion and fine-tuned ejecta direction. This also means that the occurrence rate is likely to be quite low, and that only a small fraction of the progenitor binaries may become compact LMXBs through this channel. However, the mass transfer lifetime of these binaries can be as long as $10^7$ yr, at least one order of magnitude larger than that of wide LMXBs (e.g. Justham et al. 2006). Hence the expected populations of long- and short-period BHLMXBs could still be roughly equal in size.

In the following we briefly discuss possible observational clues to rapid mass loss during a SN explosion. (1) If the SN ejecta is contaminated with stripped hydrogen from the secondary star, the SN may appear as a Type Ib or Ic SN if the collapsing star has lost most of its hydrogen or helium envelope: the spectra undergo a transformation between a hydrogen-rich Type II SN and a helium-rich, hydrogen-deficient Type Ib or a hydrogen, helium-deficient Type Ic SN. (2) After the SN and ejecta impact, the binary (if not disrupted) is likely to have a significant orbital eccentricity, at periastron the isochronicity of the SN explosion and fine-tuned ejecta direction. This also means that the occurrence rate is likely to be quite low, and that only a small fraction of the progenitor binaries may become compact LMXBs through this channel. However, the mass transfer lifetime of these binaries can be as long as $10^7$ yr, at least one order of magnitude larger than that of wide LMXBs (e.g. Justham et al. 2006). Hence the expected populations of long- and short-period BHLMXBs could still be roughly equal in size.

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### REFERENCES

Burrows A., Dessart L., Livne E., Ott C. D., Murphy J., 2007, ApJ, 664, 416
Casares J., 2006, in del Toro Iniesta J. C., Alfaro E. J., Gorgas J. G., Salvador-Sole E., eds, JENAM 2004 Astrophys. Rev., The Many Scales of the Universe. Kluwer, Dordrecht, p. 145
Chen W.-C., Li X.-D., 2006, MNRAS, 373, 305
Cheng A., 1974, Ap&SS, 31, 49
De Luca A., Caraveo P. A., Mereghetti S., Tiengo A., Bignami G. F., 2006, Sci, 313, 814
Eggleton P. P., Verbunt F., 1986, MNRAS, 220, 131
Foellmi C., Dall T. H., Depagne E., 2007, A&A, 464, L61
Fryer C. L., 1999, ApJ, 522, 413
Fryxell B. A., Arnett W. D., 1981, ApJ, 243, 994
González Hernández J. I., Rebolo R., Israeli G., Harlaftis E. T., Filippenko, A. V., Chornock R., 2006, ApJ, 644, L49
González Hernández J. I., Rebolo R., Israeli G., 2007, A&A, in press (arXiv:0705.2693)
Gualandris A., Colpi M., Portegies Zwart S., Possenti A., 2005, ApJ, 618, 845
Israelian G., Rebolo R., Basri G., Casares J., Martin E. L., 1999, Nat, 401, 142
Ivanova N., 2006, ApJ, 653, L137
Justham S., Rappaport S., Podsiadlowski Ph., 2006, MNRAS, 366, 1415
King A. R., Labow S. H., Ogilvie G. I., Pringle J. E., 2005, MNRAS, 363, 49
Lee C.-H, Brown G. E., Wijers R. A. M. J., 2002, ApJ, 575, L996
Leonard D. C., Filippenko, A. V., 2005, in Turatto M., Benetti S., Zampieri L., Shea W., eds, ASP Conf. Ser. Vol. 342, 1604-2004: Supernovae as Cosmological Lighthouses. Astron. Soc. Pac., San Francisco, p. 330
Leonard D. C., Filippenko A. V., Chornock R., Foley, R. J., 2002, PASP, 1333, 1348
Livne E., Tuchman Y., Wheeler C. J., 1992, ApJ, 399, 665
McCluskey G. E., Kondo Y., 1971, Ap&SS, 10, 464
Maccarone T. J., 2002, MNRAS, 336, 1371
Maeda K., 2006, ApJ, 644, 385
Maeda K., Nakamura T., Nomoto K., Mazzali P. A., Patat F., Hashizume I., 2002, ApJ, 565, 405
Marietta E., Burrows D. J., Fryxell B., 2000, ApJS, 128, 615
Mazzali P. A., Nomoto K., Patat F., Maeda K., 2001, ApJ, 559, 1047
Mirabel I. F., Mignani R. P., Rodrigues I., Combi J. A., Rodriguez L. F., Guglielmetti F., 2002, A&A, 395, 595
Orosz J. A. et al., 2002, ApJ, 568, 845
Pavlov G. G., Sanwal D., Teter M. A., 2004, in Camilo F., Gaensler B. M., Pavlov G. G., Sanwal D., Teter M. A., eds, Proc. IAU Symp. 218, Young Neutron Stars and Their Environments. Astron. Soc. Pac., San Francisco, p. 239
Pinsonneault M. H., Stanek K. Z., 2006, ApJ, 639, L67
Podsiadlowski Ph., Cannon R. C., Rees M. J., 1995, MNRAS, 274, 485
Podsiadlowski Ph., Rappaport S., Han Z., 2003, MNRAS, 343, 385
Remillard R. A., McClintock J. E., 2006, ARA&A, 44, 49
Ritter H., Kolb U., 2003, A&A, 404, 301
Sutantyo W., 1974b, A&A, 31, 339
Taam R. E., Fryxell B. A., 1984, ApJ, 279, 166
Tuohy I., Garmire G. P., 1980, ApJ, 239, L107
Wang L., Howell D. A., Hölöppich P., Wheeler J. C., 2001, ApJ, 550, 1030
Wang Z., Kaplan D. L., Chakrabarty D., 2007, ApJ, 655, 261
Wheeler J. C., Lecar M., McKee C. F., 1975, ApJ, 200, 145
Woosley S. E., Bloom J. S., 2006, ARA&A, 44, 507