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Limits on the spin up of stellar-mass black holes through a spiral stationary accretion shock instability

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HIGHLIGHTS

- We propose a spiral SASI as the most efficient mechanism to spin up BHs/NSs during CC.
- We show the maximum spin a PNS may acquire during CC.
- We show the maximum spin for a low mass BH is around $a_\star \lesssim 0.3$.
- We show that BHs in HMXBs may not obtain a large BH spin during CC.
- Our results suggest that hypercritical accretion may be necessary to explain the observed BH spins in HMXBs.

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ABSTRACT

The spin of a number of black holes (BHs) in binary systems has been measured. In the case of BHs found in low-mass X-ray binaries (LMXBs) the observed values are in agreement with some theoretical predictions based on binary stellar evolution. However, using the same evolutionary models, the calculated spins of BHs in high-mass X-ray binaries (HMXBs) fall short compared to the observations. A possible solution to this conundrum is the accretion of high-specific-angular-momentum material after the formation of the BH, although this requires accretion above the Eddington limit. Another suggestion is that the observed high values of the BHs spin could be the result of an asymmetry during Core Collapse (CC). The only available energy to spin up the compact object during CC is its binding energy. A way to convert it to rotational kinetic energy is by using a Standing Accretion Shock Instability (SASI), which can develop during CC and push angular momentum into the central compact object through a spiral mode ($m = 1$). Here we study the CC-SASI scenario and discuss, in the case of LMXBs and HMXBs, the limits for the spin of a stellar-mass BHs. Our results predict a strong dichotomy in the maximum spin of low-mass compact objects and massive BHs found in HMXBs. The maximum spin value ($|a_\star|$) for a compact object near the mass boundary between BHs and NSs is found to be somewhere between 0.27 and 0.38, depending on whether secular or dynamical instabilities limit the efficiency of the spin up process. For more massive BHs, such as those found in HMXBs, the natal spin is substantially smaller and for $M_{\rm BH} > 8\ M_\odot$ spin is limited to values $|a_\star| \lesssim 0.05$. Therefore we conclude that the observed high spins of BHs in HMXBs cannot be the result of a CC-SASI spin up.

1. Introduction

It is generally accepted that stellar-mass Black Holes (BHs), like neutron stars (NSs), are formed by the core collapse (CC) of a massive star ($M \gtrsim 8 M_\odot$) (Shapiro and Teukolsky, 1983). Whether a BH or a NS is formed depends mostly on whether the maximum stable mass of a NS is exceeded during CC or shortly after by fall back material. The mass cutoff between BHs and NSs is still not well known, but it is generally accepted to lie somewhere between 2.5 and 3 $M_\odot$ (Lattimer and Prakash, 2010).

If a NS is produced and its spin period is short enough ($P \sim 10$ s to 100 ms) a pulsar (PSR) is born. Theory still has difficulties explaining the observed spin rates. From the stellar-evolution point of view, models of massive stars that include angular-momentum transport due to rotationally-induced instabilities and circulations, overpredict the final spin of NSs (e.g., Heger et al., 2000). The situation changes in models that also include transport of angular momentum by magnetic torques, which do a much better job in predicting the final rotation rate of NSs (Heger et al., 2005; Suijs et al., 2008). Note however that the physics of internal angular momentum transport in stars is not yet understood (Cantiello et al., 2014; Fuller et al., 2014),

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Table 1
Physical parameters for six BH binaries (three LMXBs and three HMXBs) listed in order of increasing $a_\star$. For each system we show mass of the black hole and the companion, orbital period as well as predicted and measured Kerr parameter $a_\star$. References: (1) Steiner et al. (2011), (2) Orosz et al. (2011); (3) Shafee et al. (2006), (4) Beer and Podsiadlowski (2002); (3) Shafee et al. (2006), (5) Park et al. (2004); (6) Reid et al. (2011), Orosz et al. (2011) and Gou et al. (2011) who have new estimates of distance (from trigonometric parallax), mass and spin, however, compare to (7) Axelsson et al. (2005) who find 0.48 ± 0.01 or (8) Miller et al. (2009) who find $a_\star = 0.05$; previous estimates for masses can be found at (9) Herrero et al. (1995) and (10) Orosz (2003); (11) Liu et al. (2008), (12) Liu et al. (2010), (13) Orosz et al. (2007), (14) Pietsch et al. (2004); (15) Gou et al. (2009), (16) Orosz et al. (2009).

BH binary	$M_{\rm BH}$ $[M_\odot]$	$M_{\rm sec}$ $[M_\odot]$	$P_{\rm now}$ [days]	$a_\star$ (model)	$a_\star$ (measured)	References
LMXBs						
XTE J1550-564	9.10 ± 0.61	0.30 ± 0.07	1.5420333(24)	0.5	$0.49^{+0.13}_{-0.20}$	1,2
GRO J1655-40	5.4 ± 0.3	1.45 ± 0.35	2.6127(8)	0.8	0.65–0.75	3,4
4U 1543–47	9.4 ± 2.0	2.7 ± 1.0	1.1164	0.8	0.75–0.85	3,5
HMXBs						
M33 X-7	15.65 ± 1.45	70.0 ± 6.9	3.453014	< 0.15	0.84 ± 0.05	11,12,13,14
LMC X-1	10.91 ± 1.41	31.79 ± 3.48	3.90917(8)	< 0.15	$0.92^{+0.05}_{-0.07}$	15,16
Cyg X-1	14.81 ± 0.98	19.2 ± 1.9	5.599829	< 0.15	$> 0.97(3\sigma)$	6,7,8,9,10

and the spin rate of pre-collapse stellar cores might be determined by processes not currently included in stellar evolution calculations (Fuller et al., 2015). Regardless, the final spin of a NS can be further affected by asymmetries of the CC and/or supernova (SN) explosion (see, e.g., Wongwathanarat et al., 2013, for recent simulations). Spruit and Phinney (1998) proposed that during the SN explosion, an asymmetric kick (off the radial direction of the star), or a series of kicks, could be responsible for spinning up NSs as well as for giving them large radial velocities. More recently, Blondin and Mezzacappa (2007) discussed a mechanism that may allow NSs to be spun up during stellar-core collapse. Said mechanism relies on an instability of the accretion shock (Standing Accretion Shock Instability, SASI) which is formed after the bounce of the core during the stellar collapse. A spiral mode of this instability can lead to a spin-up of the PNS (Foglizzo and Tagger, 2000; Foglizzo, 2002; Foglizzo et al., 2007; Scheck et al., 2008; Fernández, 2010; Rantsiou et al., 2011; Hanke et al., 2013; Fernández, 2015). In this situation even an originally non-rotating progenitor could, in principle, form a rapidly spinning NS.

In this paper we study the SASI spin-up scenario and determine upper limits for the natal spin of compact objects by assuming all the available (binding) energy is transformed into kinetic rotational energy. Our results show that this mechanism (essentially, conservation of energy and angular momentum during CC) cannot explain the high spins of BHs in HMXBs.

1.1. Black holes' spin

Lee et al. (2002), Brown et al. (2007) and Moreno Méndez et al. (2011) have estimated the spin[1] of the Galactic, stellar-mass BHs where the masses and orbital periods of the binaries are relatively well constrained (some of them are included in Table 1). In their model a massive star and its companion evolve into a common-envelope phase after Case-C mass transfer (i.e., mass transfer taking place after core-He burning in the primary; Lauterborn, 1970) and the orbital separation decreases to a few $R_\odot$ after the removal of the envelope of the primary star. The mass of the companion constrains the separation of the binary at the time the BH forms, as a massive companion cannot fit in arbitrarily small orbits. Following the formalism of Zahn (1975), Zahn (1977), Zahn (1989) it is assumed that the tidal-synchronization timescale of the massive star is short enough to allow for the star to rotate synchronously with the orbital period (later confirmed numerically by van den Heuvel and Yoon, 2007). More recently, Moreno Méndez (2014) estimated the Alfvén timescales for angular momentum transport in and out of the inner layers of the star, also finding ranges in the magnetic field that allow to keep a substantial amount of angular momentum in the stellar core. Thus, the maximum spin the BH can have is constrained by tidal synchronization with the companion star at a very late stage in its evolution (see, e.g., Fig. 3 in Brown et al., 2008). This resulted in the predicted values for $a_\star$ shown in Table 1. Notice that all of the predicted and measured $a_\star$s are positive, most likely as a consequence of tidal synchronization. Besides those in Table 1, there are three more with measured Kerr parameters. GRS 1915+105, which has an $a_\star \gtrsim 0.98$ (McClintock et al., 2006; compare to the model prediction for natal spin: $a_\star \sim 0.2$); it is likely that the BH in this system accreted $\gtrsim 50\%$ of its present mass (which is currently $M_{\rm BH} \sim 15 M_\odot$) via RLOF (Moreno Méndez et al., 2011). A large mass transfer explains the present spin and its long orbital period (33.5 days). A second system is A 0620-003, with $a_\star = 0.12 \pm 0.19$ (Gou et al., 2010, compare to the predicted spin $a_\star = 0.6$); this system is harder to model given that the companion is a low-mass star ($\sim 0.7 M_\odot$). As the system may be very old, the long timescale available for angular momentum loss through different channels makes reliable estimates difficult. The third system is LMC X-3, which has a measured spin of $a_\star \lesssim 0.3$ (Davis et al., 2006), and Brown et al. (2008) estimate it may have been formed with $a_\star \simeq 0.5$ before powering up a long GRB/hypernova event. Furthermore, this model along with that of Usov (1992), has been recently employed to explain a three-peaked GRB (110709B) in Moreno Méndez et al. (2015).

Measurements of the spins of several sources have confirmed the theoretical predictions of Lee et al. (2002), Brown et al. (2007) and Moreno Méndez et al. (2011) on three Galactic sources. These are GRO J1655-40, 4U 1543–47 (Shafee et al., 2006) and more recently, XTE J1550-564 (Steiner et al., 2011). However, the predicted natal spins fall short with respect to the observed ones for BHs with massive companions (see last three rows in Table 1). Moreno Méndez et al. (2008) have addressed this issue by arguing that later accretion onto the BH can spin it up. Liu et al. (2008), Gou et al. (2009) and later Valsecchi et al. (2010) as well as Axelsson et al. (2011) argue against such a scenario based on the fact that this would require mass transfer rates above Eddington's limit. They also note that due to the large mass ratio in such binaries, mass transfer would be unstable and quickly lead to a merger, thus preventing the observation of such systems. Hence, they argue for the spin of these BHs being natal. Axelsson et al. (2014) further conclude that in the case of Cyg X-1 the spin could not be acquired previously to the formation of the BH (for similar reasons to those of Brown et al., 2007; Moreno Méndez et al., 2011), and hence, it must have been acquired during the collapse into the BH, and suggest this may have occurred through the mechanism put forward by Blondin and Mezzacappa (2007) for spinning up NSs. Meanwhile, Moreno Méndez (2011) proposed that wind Roche-lobe

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[1] $a_\star = Jc/GM^2$, where J is the total angular momentum, c is the speed of light, G is the gravitational constant and M is the mass of the BH.