Natal kicks of stellar-mass black holes by asymmetric mass ejection in fallback supernovae

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ABSTRACT
Integrating trajectories of low-mass X-ray binaries containing black holes within the Galactic potential, Repetto, Davies & Sigurdsson recently showed that the large distances of some systems above the Galactic plane can only be explained if black holes receive appreciable natal kicks. Surprisingly, they found that the distribution of black hole kick velocities (rather than that of the momenta) should be similar to that of neutron stars. Here I argue that this result can be understood if neutron star and black hole kicks are a consequence of large-scale asymmetries created in the supernova ejecta by the explosion mechanism. The corresponding anisotropic gravitational attraction of the asymmetrically expelled matter does not only accelerate new-born neutron stars by the “gravitational tug-boat mechanism”. It can also lead to delayed black-hole formation by asymmetric fallback of the slowest parts of the initial ejecta onto the transiently existing neutron star, in course of which the momentum of the black hole can grow with the fallback mass. Black hole kick velocities will therefore not be reduced by the ratio of neutron star to black hole mass as would be expected for kicks caused by anisotropic neutrino emission of the nascent neutron star.

Key words: stars: neutron – supernovae: general – black hole physics – binaries: general – X-rays: binaries – neutrinos

1 INTRODUCTION
Young neutron stars (NSs) are observed to possess space velocities in the range of $\sim 200$–$500 \, \text{km} \, \text{s}^{-1}$ on average (e.g., Lyne & Lorimer 1994; Hansen & Phinney 1997; Arzoumanian, Chernoff & Cordes 2002, Faucher-Giguère & Kaspi 2006). The fastest ones speed through interstellar space with velocities in excess of $1000 \, \text{km} \, \text{s}^{-1}$. Such eigenmotions are much faster than typical velocities of Galactic stars and cannot be explained by the breakup of binary systems as a consequence of the supernova (SN) explosion. This points to the compact remnants receiving natal kicks during their birth events. Nataal NS kicks have also been concluded from SN-remnant associations, from special characteristics of the spin and orbital parameters of several compact binaries, and from evolutionary studies of the NS binary population (e.g., Lai, Chernoff & Cordes 2001; for a review, see Lai 2001).

Observational evidence is also growing that stellar-mass black holes (BHs) might receive recoil velocities at their formation, but the conclusions drawn from the space velocities, orbital parameters, and locations of individual binaries within the Galaxy are still ambiguous. While the space velocities of some systems do not seem to require natal BH kicks, e.g., Cygnus X-1 (Nelemans, Tauris & van den Heuvel 1999) and GRS 1915+105 (Dhawan et al. 2007), or are compatible with at most a small kick (Cygnus X-1; Wong, Willems & Kalogera 2010), other systems suggest that the kicks could be appreciable, e.g., in the cases of GRO J1655-40 (Nova Sco; Brandt, Podsiadlowski & Sigurdsson 1995; Willems et al. 2005) and XTE J1118+480 (Remillard et al. 2000; Mirabel et al. 2001; Gualandris et al. 2005; Fragos et al. 2009).

Recently, Repetto, Davies & Sigurdsson (2012) considered the population of Galactic BH low-mass X-ray binaries (BH-LMXBs) as a whole instead of analysing the properties of individual systems. They modeled the formation of BH-LMXBs in the Galaxy and applied both mass-loss kicks of the binaries due to the SN explosion of the primary star and additional natal kicks obtained by the newly formed BHs. Then they integrated the trajectories of the binary systems within the Galactic potential. Comparing the synthesized BH-LMXB population with the Galactic distribution they concluded that birth kicks of the BHs are necessary to explain the large distances above the Galactic plane achieved by some binaries. The hypothesis that BHs only rarely receive a natal kick is ruled out with high significance. Moreover, by comparing results for different theoretical kick distributions, they found that BHs most likely have the same...
formed compact object, the exact value depending on still acceleration of the NS. The energy radiated in neutrinos (PNS) carries away momentum and can lead to a recoil

Anisotropic emission of neutrinos by the hot proto-NS

2 NEUTRINO INDUCED NS AND BH KICKS

The consequences of asymmetrical explosions for the kicks of BHs formed in fallback SNe will be discussed in Sect. 3.2 after a brief description of neutrino induced NS and BH recoil has been given in Sect. 2 and a discussion of NS acceleration by the gravitational tug-boat mechanism in Sect. 4.3. A summary and conclusions will follow in Sect. 5.

2.1 NEUTRINO INDUCED NS AND BH KICKS

Anisotropic emission of neutrinos by the hot proto-NS (PNS) carries away momentum and can lead to a recoil acceleration of the NS. The energy radiated in neutrinos equals the huge gravitational binding energy of the NS; this amounts to 10–20% of the rest-mass energy of the newly formed compact object, the exact value depending on still incompletely known properties of the supernuclear equation of state (EoS), which determine the compactness of the remnant (Lattimer & Prakash 2001). Since neutrinos escape with the speed of light (c), a small asymmetry of the emission can account for appreciable NS kicks. For a radiated neutrino energy \( E_\nu \), corresponding to a radial momentum \( p_\nu = E_\nu / c \), and for an emission asymmetry parameter \( \alpha_\nu \), the linear momentum transferred to the NS (opposite to the stronger neutrino-emission direction) is

\[
p_{\text{NS}} = M_{\text{NS}} v_{\text{NS}} = \alpha_\nu \frac{E_\nu}{c}.
\]

(1)

Introducing \( f_\nu \sim 0.1–0.2 \) as the ratio of the NS binding energy, \( E_\nu = E_b(M_{\text{NS}}) \), to the NS rest-mass energy, \( M_{\text{NS}}c^2 \), i.e., \( E_\nu = E_b(M_{\text{NS}}) = f_\nu M_{\text{NS}}c^2 \), the NS velocity can be written as

\[
v_{\text{NS}} = \alpha_\nu f_\nu (M_{\text{NS}}) c = 300 \left( \frac{\alpha_\nu}{0.01} \right) \left( \frac{f_\nu}{0.1} \right) \text{ km s}^{-1}.
\]

(2)

This means that an emission asymmetry \( \alpha_\nu \) of only one percent, \( \alpha_\nu \sim 0.01 \), could produce a NS kick around 300 km s\(^{-1}\).

Because of the strong gravity of the NS, however, it is extremely difficult to explain a global anisotropy of even only one percent that applies for the whole neutrino-cooling period of many seconds. Convection inside the hot PNS (i.e., below the neutrinosphere) cannot be an explanation, because the highly time-dependent pattern of convective cells (whose angular diameter roughly equals the radial depth of the convective shell) stochastically averages the associated asymmetries of the neutrinospheric emission. The value of the corresponding effective neutrino-emission anisotropy remains extremely small.

In order to define a nonstochastic, preferred direction of neutrino transport, a variety of scenarios have been proposed, mostly involving ultra-strong magnetic fields \((>10^{15}–10^{16} \text{ G})\) in the interior of the nascent NS. If such fields could possess a strong dipolar component (which may be questioned because of the violent, nonstationary, high-multipolar convective mass motions in the hot PNS), or if they could develop a broken mirror symmetry by rapid differential rotation, this might lead to an enhancement of the neutrino emission in one hemisphere, e.g., either by the direct \( B \)-dependent modifications of the neutrino opacities of nucleonic matter (Bisnovatyi-Kogan 1996; Arras & Lai 1999) or by their impact on active-sterile neutrino-flavor oscillations (e.g., Fuller et al. 2003; Kusenko 2009) or on the neutrino emission from a hypothetical quark phase in the core of the compact remnant (Sagert & Schaffner-Bielich 2008). All of these scenarios, however, invoke more than a single ingredient of uncertain physics and must thus be considered as highly speculative.

Nevertheless, neutrino-induced kicks by the mentioned scenarios cannot be rigorously discarded and observational tests of the associated predictions are extremely desirable. In this context the implications of the population of Galactic BH-LMXBs for BH kicks are very interesting.

BH formation in a stellar core-collapse event occurs after a transient period of NS stability, during which the NS loses energy by neutrino emission. The existence of such a phase is crucial in the context of the neutrino-driven explosion mechanism, where the neutrinos radiated by the NS deposit the energy that initiates and powers the expulsion of the outer stellar layers in the SN. A BH eventually may form when the NS becomes gravitationally unstable due to a phase transition that softens the EoS at supranuclear densities. Alternatively, instead of a reduction of the maximum stable NS mass by such an EoS softening, the collapse to a BH can be triggered by accretion of gas onto the NS until
its mass exceeds the stability limit. A SN explosion does not necessarily accompany such a BH formation event.\(^1\) In the case of a successful explosion, however, BH formation can happen by the later fallback of initially outward moving matter that does not maintain a velocity larger than the escape velocity to become unbound. Such a partial reimplosion of the star may be triggered by reverse shocks which form in phases when the SN shock slows down and which decelerate the expanding stellar shells in the inner regions of the SN.

When a BH forms via one of these paths the energy radiated in neutrinos is bounded from above by the gravitational binding energy of the NS with the maximum possible mass: \(E_\nu \leq E_b(M_{NS}^{\text{max}}) = f_\nu(M_{NS}^{\text{max}}) M_{NS}^{\text{max}} c^2\). Using this in Eq. (1) and replacing there the NS mass and velocity by \(M_{BH}\) and \(v_{BH}\), respectively, we find that the velocity of the BH is constrained by

\[
v_{BH} \leq \alpha_v f_\nu(M_{NS}^{\text{max}}) \frac{M_{NS}^{\text{max}}}{M_{BH}} c \leq \frac{M_{NS}^{\text{max}}}{M_{BH}} v_{NS}^{\text{max}}. \tag{3}\]

Since \(f_\nu(M_{NS})\) and \(f_\nu(M_{NS}^{\text{max}})\) are of similar size and there is no reason why NSs that ultimately collapse to a BH should radiate neutrinos with a systematically larger asymmetry \(\alpha_v\), Eq. (3) compared to Eq. (2) implies that BHs would receive kicks which are generally reduced by roughly a factor \(M_{NS}/M_{BH}\) compared to those of NSs. This is in conflict with the results obtained by Repetto et al. (2012). We therefore conclude that observational evidence for natal BH kicks larger than the maximum kicks of the reduced-velocity distribution of NSs disfavors the neutrino-induced kick mechanism, at least as an explanation of the BH recoil motions. Moreover, the high velocities of BH-LMXBs also exclude that the BHs have formed without associated SN explosions, because in this case the natal BH kicks could only result from anisotropic neutrino emission and their velocities would have to be limited by Eq. (3).

In the sequence of arguments used above the assumption was made that the neutrino emission essentially stops once the BH has formed. This is a viable assumption as long as the fallback matter accreted onto the newly formed BH has little angular momentum, because matter that collapses essentially radially into a BH falls inward too quickly to efficiently lose energy by radiating neutrinos. With sufficiently large angular momentum, however, the fallback matter could assemble into an accretion disk around the BH and thus would continue to produce neutrinos at a significant rate. A corresponding hemispheric emission asymmetry would affect the BH kick constraint of Eq. (3).

\(^1\) The exact value of the maximum NS mass is currently not known because of our incomplete understanding of the supranuclear EOS. For a cold NS it is certainly above \((2.01 \pm 0.04) M_\odot\) (Antoniadis et al. 2013) and probably lower than \(~3 M_\odot\), which implies that the baryonic mass of the hot, accreting object can be some ten percent higher before it becomes gravitationally unstable.

\(^2\) In the context of this paper the term SN is used for stellar explosions driven by a successfully revived core-bounce shock. Low-velocity mass loss from the progenitor-star surface in response to the reduced gravitating mass due to the neutrino emission at the stellar center (Lovegrove & Woosley 2013) has no relevance for the presented discussion.

However, the angular momentum needed to keep matter on orbits around a BH is huge. For Keplerian motion near the innermost stable circular orbit, where the specific angular momentum \(j\) has an absolute minimum, one estimates that in the case of a Schwarzschild BH \(j_{\text{esc}(M_{BH})} \approx 5 \times 10^{15} (M_{BH}/3 M_\odot) \text{ cm s}^{-1}\) is necessary. Massive, BH forming stars, at least at solar metallicity, are unlikely to retain such amounts of angular momentum because of mass loss and the increased angular momentum loss mediated by magnetic torques (Heger, Woosley & Spruit 2005; Langer 2012). Similarly, also hydrodynamic instabilities during the pre-explosion phase like the spiral standing accretion shock instability (Blondin & Mezzacappa 2007; Fernández 2010, Hanke et al. 2013) are not likely to build up sufficient angular momentum in the region around the initial mass cut for stabilizing later fallback material in a disk around the BH. The conclusion arrived at above should therefore remain valid even if angular momentum plays a role at some level.

3 ASYMMETRIC MASS EJECTION AND COMPACT REMNANT KICKS

The explosion mechanism of core-collapse SNe is nowadays understood to be intrinsically multidimensional. This is suggested by observations, which require large-scale mixing and asymmetries in the exploding stars (e.g., Leonard et al. 2006), and by theoretical considerations, which fail to explain the onset of the SN blast with spherically symmetric models except in the case of the lowest-mass (oxygen-neon-magnesium-core) progenitors (see, e.g., Janka 2012 and Burrows 2013 for reviews). An asymmetric onset of the explosion will lead to anisotropic mass ejection. If associated with an anisotropic distribution of the radial momentum in the outflow, total momentum conservation implies that the NS must obtain a kick with linear momentum opposite to that of the ejected mass in the rest frame of the progenitor star.

The exact mechanism that launches the SN shock wave and creates the asymmetry of the energy and mass distribution in the ejecta is not of crucial relevance; the underlying physics of the NS acceleration is generally valid independent of the specific processes that power the blast wave. The driving mechanism could be neutrino-energy deposition, magnetohydrodynamic effects, the acoustic mechanism (for a recent review of these possibilities, see Janka 2012 and references therein) or jittering jets (Papish & Soker 2011), and the mass-ejection anisotropy may not only be caused by hydrodynamic instabilities that develop during the SN explosion but might also result from pre-collapse asymmetries in the SN progenitor star (Arnett & Meakin 2011). The transfer of momentum between ejecta and NS can happen directly through hydrodynamic forces and indirectly through long-range gravitational forces. These possibilities are schematically illustrated in Fig. 1.

3.1 NS acceleration by the gravitational tug-boat mechanism

In the context of neutrino-driven SN explosions, the acceleration of the newly formed NS by asymmetrical mass ejection was demonstrated with 2D hydrodynamic simulations...
by Scheck et al. (2004, 2006) and further explored by Nordhaus et al. (2010, 2012). Simulations by Wongwathanarat et al. (2010, 2013) have provided confirmation of the kick scenario also in three dimensions. A detailed discussion of the underlying physics was provided by Wongwathanarat et al. (2013; see also Nordhaus et al. 2010). The fundamental aspects of asymmetry creation and NS repulsion are summarized here on the basis of the neutrino-heating mechanism as internal explosion energy is converted to kinetic energy by hydrodynamic forces in the accelerating SN blast. The corresponding NS acceleration is directed towards the asymmetrically distributed ejecta. The PNS experiences a persistent traction that is exerted by the anisotropic gravitational attraction of the asymmetrically distributed ejecta. Accretion to the PNS therefore decays and the transition to the neutrino-driven wind phase takes place, during which the PNS continues to lose mass at a low and declining rate ($<10^{-3} - 10^{-4} M_{\odot} \text{s}^{-1}$) in an essentially spherically symmetric supersonic outflow. This outflow is driven by the energy that neutrinos escaping from the hot PNS deposit in the layers adjacent to the neutrinosphere (Duncan, Shapiro & Wasserman 1986; Qian & Woosley 1996).

Accretion downflows and rising bubbles can directly transfer momentum to the NS by hydrodynamic effects (Janka & Müller 1994). Because of the strongly time dependent and nonstationary flows before and during the initiation of the explosion, however, the NS is bounced back and forth in varying directions and can attain only small recoil velocities (at most around $100 \text{ km s}^{-1}$) in multi-dimensional simulations of this early postbounce phase (e.g., Fryer 2004; Fryer & Young 2007). Once the explosion sets in and the asymmetry pattern of the ejecta becomes frozen in, however, significant linear momentum in a certain direction can build up in the compact remnant (as visualized in the right panel of Fig. 1). This NS recoil points away from the direction of strongest mass ejection. In contrast to such a hydrodynamic acceleration associated with the accretion downdrafts and anisotropic outflows, the spherically symmetric neutrino-driven wind does not contribute to the NS recoil on any significant level. Instead, the compact remnant experiences a persistent traction that is exerted by the anisotropic gravitational attraction of the asymmetrically distributed ejecta. The NS velocity grows at the expense of ejecta momentum, but the associated loss of momentum in the outward moving ejecta can be compensated by their continuous reacceleration as internal explosion energy is converted to kinetic energy by hydrodynamic forces in the accelerating SN blast. The NS and the towing high-density ejecta clumps can also be considered as a mass entity that moves jointly in a shared gravitational trough and interacts hydrodynamically (and

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**Figure 1.** Schematic visualization of SN mass ejection and compact remnant kicks. In the left image the ejecta are spherically symmetric and no recoil is imparted to the central object. Asymmetric mass ejection must lead to compact remnant motion with the opposite linear momentum (middle panel). The momentum can be transferred by gravitational forces and by direct hydrodynamical forces in the case of accretion. The latter are crucial when the proto-neutron star is accreting fallback matter to collapse to a black hole (right panel). (Image taken from Scheck et al. (2006); reproduced with permission ©ESO.)
gravitationally) with the surrounding SN material, similar to a sailing ship that is blown by the wind and is pulling a dinghy on a tow line.

The long-distance gravitational coupling between compact remnant and dense, slowly expanding ejecta is the most efficient contribution to the long-lasting acceleration of the newly formed NS. In 3D simulations this gravitational tugboat mechanism was shown to be able to accelerate the NS to velocities in excess of 700 km s$^{-1}$ over timescales of many seconds (Wongwathanarat et al. 2010, 2013), and analytic estimates (Wongwathanarat et al. 2013) as well as 2D simulations (Scheck et al. 2006) suggest that in extreme cases more than 1000 km s$^{-1}$ are well possible.

3.2 BH acceleration in fallback supernovae

Asymmetric mass ejection and the associated acceleration of the compact remnant by hydrodynamical and gravitational interaction has interesting implications in the case of BH formation in fallback SNe, i.e. in SN explosions where the energy injected to the blast wave is not sufficient to unbind the whole stellar mantle and envelope. In this case a larger fraction of the progenitor will fall back to the newly formed NS after its initial expansion has been slowed down by reverse shocks that originate when the outgoing SN shock wave decelerates in regions where the density gradient is more shallow than $\rho \propto r^{-3}$ (e.g., Kifonidis et al. 2003). If sufficiently massive, the fallback will trigger the delayed collapse of the NS to a BH. The BH in LMXBs must have gained its mass by such a massive fallback in the course of the SN explosion of the primary star.

As described in Sect. 3.1 the PNS in an asymmetric explosion is accelerated mainly due to the gravitational attraction of the slowest-moving parts of the ejecta. The gravitational interaction between compact remnant and the innermost ejecta also determines the fallback in the SN. Therefore the fallback is likely to occur preferentially in the directions where the explosion is weaker, whereas the matter with the highest expansion velocities has the best chance to escape from the gravitational influence of the central object. This anisotropic fallback will enhance the momentum asymmetry of the SN mass ejection, thus increasing the kick velocity of the compact remnant. According to the arguments given in Sect. 3.1 the corresponding additional acceleration of the accretor is mediated by hydrodynamical and gravitational forces associated with the anisotropic infall of the fallback matter (Fig. 1 right panel). Since the asymmetry of the fallback should correlate with the momentum asymmetry of the initially (i.e., after the saturation of the NS kick and prior to the fallback) expanding SN matter, the momentum of the BH forming remnant must be expected to increase with the fallback mass. From this scenario one therefore expects a BH momentum distribution that grows with the BH mass, or, in other words, a velocity distribution of BHs which may, or, in other words, a velocity distribution of BHs which may be similar to that of NSs and which is not reduced by the ratio of NS to BH mass.

In order to make the argument more transparent and formal, let us consider a simple toy model, in which the initial explosion ejecta have a hemispheric asymmetry with mass $m_+$ and average velocity $v_+$ in one hemisphere and $m_-$ and $v_-$ in the other such that $0 < v_- \lesssim v_+$ and $m_- \lesssim m_+$ (see Fig. 1 middle panel). We can then write for the momenta carried (in opposite directions) by the ejecta and by the recoiled NS:

$$p_{\pm} = p_{\text{NS}} = m_+ v_+ - m_- v_- = \alpha \bar{v}_{\pm} M_{\text{ej}}.$$  

(4)

Here $M_{\text{ej}} = m_+ + m_-$ is the total ejecta mass, $\bar{v}_{\pm} = (m_+ v_+ + m_- v_-)/M_{\text{ej}}$ the average ejecta velocity, and $\alpha = (m_+ v_+ - m_- v_-)/(m_+ v_+ + m_- v_-)$ the momentum asymmetry of the ejecta.

Let us now assume that a mass $M_{\text{fb}}$ falls back to the compact remnant and is added to the initial PNS mass, $M_{\text{NS}}$, to yield a BH mass of

$$M_{\text{BH}} = M_{\text{NS}} + M_{\text{fb}},$$  

(5)

which grows linearly with the accreted mass. If the fallback mainly affects the most slowly expanding ejecta (as reasoned above), the initial ejecta component $m_-$ is reduced to $m'_- = m_- - M_{\text{fb}}$ (primed quantities denote the state after the fallback, unprimed ones correspond to the conditions prior to the fallback). The momenta of the expelled SN matter and of the BH after the fallback are:

$$p_{\pm}' = p_{\text{BH}} = m_+ v_+ - (m_- - M_{\text{fb}}) v_- = p_{\text{NS}} + M_{\text{fb}} v_-.$$  

(6)

This means that not only the mass of the BH but also the BH momentum increases with the fallback mass and that the BH momentum exceeds that of the predecessor NS. Although the ejecta mass of the SN is reduced when gas is gravitationally captured again by the accreting compact object, i.e., $M_{\text{ej}}' = M_{\text{ej}} - M_{\text{fb}}$, the asymmetry of the mass ejection as well as the average velocity of the ultimately escaping gas will grow (Fig. 1 right panel). Linearizing the corresponding quantities for $M_{\text{fb}}/M_{\text{ej}} \ll 1$ (which implies even an underestimation of the extreme conditions when the fallback affects a major fraction of the stellar mass) one obtains for the momentum asymmetry parameter:

$$\alpha' \sim \alpha + (1 + \alpha) \frac{v_-}{\bar{v}_{\pm}} \frac{M_{\text{fb}}}{M_{\text{ej}}},$$  

(7)

and for the average ejecta velocity:

$$v_-' \sim \bar{v}_{\pm} + (\bar{v}_{\pm} - v_-) \frac{M_{\text{fb}}}{M_{\text{ej}}}. $$  

(8)

Since $\bar{v}_{\pm} - v_- > 0$ the correction terms depend on $M_{\text{fb}}$ in both Eqs. (7) and (8) are positive, which means that the primed quantities are larger than the unprimed ones.

Combining Eq. (4) ($p_{\pm} = p_{\text{NS}}$) with Eqs. (5) and (6), one obtains for the BH kick velocity

$$v_{\text{BH}} = \frac{M_{\text{NS}}}{M_{\text{BH}}} v_{\text{NS}} + \frac{M_{\text{fb}}}{M_{\text{BH}}} v_- \approx \frac{M_{\text{NS}}}{M_{\text{BH}}} v_{\text{NS}} + v_-,$$  

(9)

where the transformation for the inequality makes use of $M_{\text{BH}} \sim M_{\text{fb}} \gg M_{\text{NS}}$. Equation (9) compared to Eq. (3) constitutes the main difference between BH kicks as a consequence of explosion asymmetries in fallback SNe and BH kicks associated with NS kicks caused by anisotropic neutrino emission. While the latter are limited by the maximum velocity that NSs can receive, reduced by a factor of NS to BH mass, explosion asymmetries do not imply such a constraint for the BH velocities. The fallback-SN scenario for accelerating stellar BHs is therefore compatible with the large natal BH kicks concluded by Repetto et al. (2012) from their population synthesis analysis of the observed distribution of Galactic BH-LMXBs.
It should be noted, however, that in the discussed scenario the distribution of natal BH recoil velocities is not predicted to be the same as the natal NS velocity distribution. If $M_{\text{BH}} \gg M_{\text{NS}}$, the second term depending on $v_-$ in Eq. (9) yields the dominant contribution to the BH velocity $v_{\text{BH}}$. The distribution of BH kick velocities therefore needs to be determined by a large set of 3D supernova simulations for a wide variety of progenitor stars, for which the expansion asymmetry and the long-time evolution of the anisotropic fallback are followed over periods of possibly days. While such simulations are currently not available, one can still estimate the magnitude of the corresponding BH kick velocities.

In order to become gravitationally unbound, SN debris has to expand with velocities in excess of the escape velocity, otherwise it will be gravitationally captured by the central compact remnant. Fallback will therefore be inherent to collapse where SN debris becomes less than the escape velocity, i.e., if $v_\prime < v_{\text{esc}}$. Since the passage through a reverse shock decelerates the expansion velocity by a factor that is roughly equal to the inverse of the density jump in the reverse shock, $v_\prime/v_- \approx \rho/\rho \equiv \beta$ with $4 \leq \beta \leq 7$ depending on the equation of state of the SN gas, the condition for initial ejecta being swallowed by the NS results from the condition for the ejecta to be unbound by a factor $\beta$.

\begin{equation}
\begin{aligned}
\nu_- < \beta v_{\text{esc}}(r) & \approx \beta \sqrt{2GM(r)/r} \\
& \approx 1130 \left(\frac{\beta}{4}\right) \left(\frac{M}{3M_\odot}\right)^{1/2} \left(\frac{r}{10^{12}\text{ cm}}\right)^{-1/2} \text{ km s}^{-1}. \tag{10}
\end{aligned}
\end{equation}

Here $\beta = 4$ for a nonrelativistic ideal gas was used, a value of $3M_\odot$ corresponding to a “seed BH mass” was chosen for the normalization of the gravitating mass, and a radius of $10^{12}$ cm constitutes an approximate lower bound of the radial scale where the strong reverse shock from the He/H composition interface begins to affect the ejecta expansion (see, e.g., Kifonidis et al. 2003). The result of Eq. (10) shows that extreme conditions (namely, highly asymmetric fallback as assumed in the sequence of steps leading to Eq. (9)) are able to produce BH kick velocities that can compete with the greatest measured space velocities of NSs. BH kicks of several $100 \text{ km s}^{-1}$ appear sufficiently large to be consistent with anisotropic fallback in SNe.

4 SUMMARY AND CONCLUSIONS

I have argued that explosion asymmetries created by the SN mechanism are likely to explain not only the natal kicks of NSs but also those of BHs. Clumpy and inhomogeneous SN ejecta exert long-duration, anisotropic gravitational forces on the NS and can thus accelerate the compact object over timescales of seconds to velocities of many hundred kilometers per second (Scheck et al. 2004, 2006; Nordhaus et al. 2010, 2012; Wongwathanarat et al. 2010, 2013). Similarly, the slowest-moving parts of the ejecta, especially when reverse shock decelerate the expanding SN flow, can be gravitationally recaptured by the NS. The anisotropic fallback of SN matter may not only trigger the collapse of the NS to a BH but also allow the momentum of the compact remnant to increase significantly proportionally to the accreted (and thus BH) mass (Eqs. [8] and [9]), and the BH kick velocities can become similarly large as those of NSs (Eqs. [8] and [9]). This fallback-SN scenario for BH formation and recoil is therefore compatible with the results of Repetto et al. (2012), according to which large BH natal kicks are required by the wide spread of the observed distribution of BH-LMXBs around the Galactic plane.

In contrast, momentum-conserving BH kicks, for which the BH velocity would be reduced by a factor $M_{\text{NS}}/M_{\text{BH}}$ compared to NS recoil velocities, are ruled out by the study of Repetto et al. (2012) with high statistical significance. This strongly favors the possibility that BH kicks are simply inherited from their predecessor NSs, because such a connection would constrain the BH momentum by the maximum possible NS momentum (Eq. 3). In particular, it disfavors scenarios, in which intrinsic NS properties like anisotropic neutrino emission caused by strong magnetic dipolar fields are responsible for the NS acceleration without asymmetric mass ejection playing any important role for the kick. In a special variant of this scenario (assuming a powerful neutrino-induced BS kick early after core bounce), Fryer & Kusenko (2006) found that the neutrino-heating mechanism initiates a stronger mass ejection of the SN explosion in the direction of the recoil motion of the NS. Such a hypothetical situation, however, appears to be in conflict with the results of Repetto et al. (2012). Because fallback must preferentially occur on the weaker side of the explosion, the increasing momentum of the remaining ejecta can only be balanced if the BH that forms by the fallback accretion is accelerated opposite to the movement of the NS. This effect must be expected to grow with the initial NS kick and to result in a significant damping of the final BH motion. It is important to recognize that in the scenario of Fryer & Kusenko (2006) the anisotropic neutrino emission carries momentum and that the same amount of momentum in the opposite direction has to be shared by the compact remnant and the SN ejecta.

A quantitative theoretical determination of the velocity distribution of BHs in the fallback-SN scenario beyond the simple upper-limit estimate of Eq. (10) will require long-time 3D hydrodynamic explosion modeling including the fallback evolution for a large set of progenitor stars. The gravitational tugboat mechanism for NS acceleration has been shown to lead to the observational prediction that iron-group elements and explosively produced intermediate-mass nuclei heavier than $^{28}$Si are ejected by the SN with significant enhancement in the hemisphere of the stronger explosion, i.e., opposite to the direction of a large NS kick (Wongwathanarat et al. 2013). In the case of BH formation in anisotropic fallback SNe such an effect should even be enhanced. Strong hemispheric asymmetries of the heavy-element distribution in SN remnants may thus provide observational hints for highly aspherical explosions and therefore for large kicks of the compact remnant, even if the latter and its space velocity might be difficult to measure.

A tight connection between BH kicks and SN explosion asymmetries implies that the BHs in fast-moving BH-LMXBs have to originate from fallback SNe. BHs formed without accompanying SN explosions can be recoiled only by anisotropic neutrino emission, which might occur during the neutrino cooling of a transientsly stable NS. In this case the corresponding BH velocities would be limited by the value of Eq. (3), in conflict with the analysis by Repetto et al. (2012). Accepting the inefficiency of neutrino-induced
BH kicks one can further conclude that stellar collapse to a BH without a SN explosion should lead to BHs with very low velocities, and a bimodality of the BH velocity distribution seems possible. The relative population of the low-velocity and high-velocity components should depend on the (still unknown) probability of BH formation without associated SN relative to BH formation in fallback SNe.

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