Spin-perpendicular kicks from evanescent binaries formed in the aftermath of rotational core-collapse and the nature of the observed bimodal distribution of pulsar peculiar velocities

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ABSTRACT. We argue that if core collapse leads to the formation of a rapidly rotating proto-neutron star core or a fizzler surrounded by fall-back material, a lighter proto-neutron star forms around the main star moving in a super-close orbit, as an end result of a fully developed dynamical non-axisymmetric instability. Tidal mass exchange (even through a common envelope phase) propels the lighter star toward the minimum stable mass for a proto-neutron star, whereupon it explodes and the short-lived binary disrupts. The star that remains, a newly born neutron star (or a black hole) acquires a recoil velocity $V_{\text{kick}}$, according to the law of conservation of linear momentum. A noteworthy feature of this process is that the final kick is determined by nuclear physics, and produces in reality a widespread range in peculiar velocities, up to the highest values observed in the pulsar sample $\gtrsim 1600\,\text{km}\,\text{s}^{-1}$. Interestingly, $V_{\text{kick}}$ scales with the mass $M$ of the star that remains as $M^{-2/3}$. The kick, lying in the orbital plane of the binary, is expected to be nearly perpendicular to the spin vector of the post-collapse unstable core, and thus of the neutron star newly formed. Nearly spin-perpendicular kicks of large amplitude are required to explain the observations of geodesic precession in double neutron star binaries such as B1913+16. On the contrary, spin-kick alignment has been claimed for the Vela and Crab pulsars whose transverse speeds are $\gtrsim 70$ and $\sim 170\,\text{km}\,\text{s}^{-1}$ respectively. We suggest that the larger kick component, when present in a pulsar, results from the formation and disruption of an evanescent binary, and is perpendicular to the spin axis; the smaller kick component is associated some other mechanism that leads to less vigorous kicks, predominantly parallel to the spin axis because of phase averaging. This could give rise to a bimodal distribution in the peculiar velocities of neutron stars, as it is observed in the pulsar sample. This scenario may explain the run-away black hole GRO J1655-40, the first to show evidence for a natal kick.

1. Introduction

Radio pulsars have peculiar space velocities between $\approx 30\,\text{km}\,\text{s}^{-1}$ and $\approx 1600\,\text{km}\,\text{s}^{-1}$, significantly greater than those of their progenitor stars. The highest speed is from the Guitar Nebula pulsar (Cordes & Chernoff 1998), while the lowest has been recently measured for B2016+28 by Brisken et al. (2002) from very accurate VLBA pulsar parallaxes. An early explanation for the large space velocities of pulsars called for recoil in a close binary that becomes unbound at the time of (symmetric) supernova explosion. Now, a number of observations hint at a natal origin of these high space velocities, or at a combination of orbital disruption and internal kick reaction (when the progenitor lives in a binary). Evidence for a kick at the time of neutron star birth is now found in a variety of systems, e.g., in double neutron star binaries such as B1913+16 (Weisberg, Romani, & Taylor 1989; Cordes, Wasserman, & Blaskiewicz 1990; Wex, Kalogera & Kramer 2000) where misalignment between the spin and orbital angular momentum axes indicates velocity asymmetry in the last supernova.

Among the physical processes that have been proposed to account for the kick impulses at birth are large-scale density asymmetries seeded in the pre-supernova core (leading to anisotropic shock propagation), asymmetric neutrino emission in presence
of ultra-strong magnetic fields (see Lai, Chernoff, & Cordes 2001 for a review), or off-centered electromagnetic dipole emission from the young pulsar (Harrison & Tademaru 1975). However, none of these mechanisms can explain kicks as large as \( \sim 1600 \text{ km s}^{-1} \).

A further interesting, yet unexplained, statistical property of pulsars has been pointed out by Arzoumanian, Chernoff and Cordes (2002). They find that the pulsar peculiar velocity distribution function is bimodal, i.e., it is described by two almost equally populated Gaussian components with mean velocities of 90 km s\(^{-1}\) (the fast pulsars) and 500 km s\(^{-1}\) (the very fast pulsars), respectively. This suggests that two distinct physical mechanisms are responsible for this bimodality, and in this proceeding we try to depict a scenario that may account for this dichotomy.

In a recent paper (Colpi & Wasserman 2002) we reconsidered the idea first put forward by Imshennik & Popov (1998) that, in the collapse of a rotating core, one or more self-gravitating lumps of neutronized matter may form in close orbit around the central nascent neutron star, transfer mass in the short lived binary, and ultimately explode, causing the remaining, massive neutron star to acquire a substantial kick velocity, as high as the highest observed. The light member explodes as mass transfer drives it below the minimum stable mass (against radial perturbations) for a neutron stars. Stability is lost upon decompression by the \( \beta \)-decaying neutrons and nuclear fissions by radio-active neutron-rich nuclei that deposit energy driving matter into rapid expansion (Colpi, Shapiro & Teukolsky 1989, 1993; Blinnikov et al. 1984, 1990; Sumiyoshi et al. 1998). The kick originates from the orbital motion of this evanescent super-close binary. Along similar lines Eichler & Silk (1992) attributed the largest kicks of pulsars to gravitational ejection of fragments formed during rotationally unstable collapse.

We have studied several effects that may mitigate the magnitude of the kick, such as gravitational bending of the exploding debris, and rotational averaging of the momentum impulse. A point that was previously overlooked is that the minimum mass of hot still lepton-rich matter is much higher than the value for cold catalyzed matter, and this opens new evolutionary pathways (we refer to Colpi & Wasserman 2002 for details).

### 2. Light fragments around proto-neutron stars

#### 2.1. Dynamical rotational non-axisymmetric instabilities

Formation of a light companion around a main body implies breaking of spherical and axial symmetry in the collapse of post-collapse phases. During dynamical collapse, unstable bar modes can grow in a fluid that may end with fragmentation. However this is known to occur only if the core contracts almost isothermally (Bonell 1994), but collapse in type II supernovae is far from isothermal so that instabilities of this type do not have time to grow (Lai 2000). Can fragmentation/fission be excited after the proto-neutron star core has formed? Rapid rotation in equilibrium bodies is known to excite non-axisymmetric dynamical instabilities. Interestingly, core collapse simulations of unstable rotating iron cores (Heger, Langer & Woosley 2000; Fryer & Heger 2000) or polytropes (Zwerger & Muller 1997) indicate that proto-neutron stars, soon after formation, can rotate differentially above the dynamical stability limit set when the rotational to gravitational potential energy ratio \( T_{\text{rot}}/|W| \) exceeds \( \sim 0.26 \). Strong non-linear growth of the dominant bar-like deformation (\( m = 2 \)) is seen in these cores (described as polytropes by Rampp, Muller, & Ruffert 1998). The bar evolves, producing two spiral arms that drain the core’s excess angular momentum outwards. A further possibility that we would like to mention here refers to the case of *fizzlers*, temporary equilibrium bodies supported almost entirely by rotation, which are driven dynamically unstable against bar-like modes by deleptonization of hot nuclear matter on timescales of \( \sim 1 – 10 \text{ sec} \) (Imamura, & Durisen 2001), producing spiral patterns around a central core.

In all these above calculations however there is no sign of fission/fragmentation into
separate condensations. How can a double or multiple system form from a bar-unstable core or fizzler? According to Bonnell’s picture (1994), the evolution of the bar instability is more complex, in reality. If the rapidly spinning proto-neutron star core or fizzler goes bar unstable when surrounded by a fall-back disk, then matter present in the bar-driven spiral arms interacts with this material. The sweeping of a spiral arm into fall-back gas can gather sufficient matter to condense, by strong cooling and deleptonization, into a (or a few) fragments of neutronized matter. This occurs because the $m = 1$ mode grows during the development of the $m = 2$ mode. The $m = 1$ mode causes the off-centering of one spiral arm which then sweeps up more material on one side than the other during continuing accretion. The condensation may eventually collapse into a low mass proto-neutron star fragment or in a few fragments of material. This has never been proved numerically.

2.2. Triggering explosion at the minimum mass limit

If a light (proto-)neutron star forms around the main central body, which limits can be imposed on its mass? Cooling plays a key role in addressing these questions. Goussard, Haensel & Zdunik (1998), and Strobel & Weigel (2001) have shown that the value of the minimum stable mass $m_{\text{mmc}}$ for a neutron star (located at the turning point in the mass-radius relation of spherical non-rotating equilibria) is a function of the temperature: it varies from $\gtrsim 1M_\odot$ at 50-100 milliseconds after core bounce (setting the actual value of the mass of the central neutron star), to $\sim 0.7M_\odot$ after $\sim 1$ second, down to $\sim 0.3M_\odot$ after 30 seconds, reaching the value of $\sim 0.09235M_\odot$ for cold catalyzed matter ($T < 1$ MeV) several hundred seconds later. Thus, the condensation of nuclear matter gathered in the spiral arm by the instability may become self-bound if its mass $m$ is above the minimum corresponding to that particular temperature. Once formed it is stabilized against expansion by cooling.

The value of $m$ and of the mass ratio $q = m/M$ in the binary (with $M$ the heavier of the two stars) remains unpredictable to us at this level, so we may just depict three possible scenarios for the formation and evolution of this evanescent binary: case (A) when the instability sets after few hundreds of milliseconds or a second after core bounce and binary formation occurs so that $m \gtrsim 0.7M_\odot$ (implying a pre-existing iron core of large mass if the primary is as massive as $1.4M_\odot$); case (B) when a lighter star with $m \simeq 0.2 - 0.4M_\odot$ forms around a main body after several seconds or tens of seconds from core bounce or after fizzler destabilization (occurring on this time scale); case (C) when cooling is sufficiently advanced that the minimum mass approaches its asymptotic value and the binary companion can have $m \lesssim 0.2M_\odot$.

3. Neutron star kicks

The magnitude of a natal kick in (A) is difficult to estimate and we must await for realistic simulations of core collapse. We note that the evolution in this case might be similar to that described in coalescing neutron star binaries with unequal masses (see Rosswog et al. 2000) where it has been shown that large kicks can be acquired as a consequence of mass loss via strong winds.

In cases (B) and (C), one factor that could lower the final neutron star speed is the finite velocity of the ejecta. Colpi, Shapiro & Teukolsky (1993) have shown that in the dynamical phase of the explosion the ejecta can attain speeds $w_0$ varying from 10,000 to $\sim 50,000$ km s$^{-1}$. These speeds are close to the escape velocity from the binary and therefore the final kick imparted to the remaining neutron star may be influenced substantially by gravitational deflection of the ejecta, and velocity phase averaging during the explosion. A further complication is the rapid decay of the orbit separation following unstable mass transfer and emission of gravitational waves. This may lead to coalescence before any mass is ejected above escape velocity.
Pulsars, AXPs and SGRs with BeppoSAX

Fig. 1. Solid lines show the neutron star kick velocity $V_{\text{kick}}$ as a function of the speed of the ejecta $w_o$, for case (C) when the light star explodes with a mass $m_{\text{expl}} \sim 0.3M_\odot$ (lower curve before crossover) and $m_{\text{expl}} = m_{\text{mmc}} = 0.09M_\odot$ (upper curve before crossover). The dash-dotted line refers to case (B) for a warm star with $m_{\text{mmc}} = 0.3M_\odot$.

In binary mass transfer scenarios (cases B, C), the maximum kick velocity $V_{\text{kick,max}}$ is determined approximately from the value of the relative orbital velocity between the stars at the time the light donor loses its stability $V \simeq (GM/r_{\text{expl}})^{1/2}$ driven by Roche lobe spill-over: explosion can occur either when the light star reaches $m_{\text{mmc}}$ after a phase of stable mass transfer, or at higher mass $m_{\text{expl}}$ if mass transfer is unstable (see Colpi & Wasserman 2002). The maximum kick is thus given by

$$V_{\text{kick,max}} \simeq \frac{m_{\text{mmc}}}{(m_{\text{mmc}} + M)} V \simeq \frac{0.68G^{1/2}m_{\text{mmc}}^2}{m_{\text{expl}}^{f-1/6}[R(m_{\text{expl}})]^{1/2}} M^{-2/3}$$  \hspace{1cm} (1)

where $R(m_{\text{expl}})$ and $m_{\text{expl}}$ are the radius and mass of the star at the time of explosion ($f < 1$). Roche lobe spill-over imposes $V_{\text{kick,max}} \propto M^{-2/3}$, as separation $r_{\text{expl}} \propto M^{1/3}$ in contact binaries. In case (B), the warmer unstable proto-neutron star always suffers unstable mass transfer and the system may enter a phase of common envelope evolution. In this case we expect that the star develops an unstable core of mass $m \approx m_{\text{mmc}}(T)$, while losing its envelope, and explodes on its own dynamical time before coalescence of the two stars in completed over $\sim$ one orbital period. Ejection of part of the envelope enshrouding the system may provide an additional thrust to the merged object.

In Figure 1, $V_{\text{kick}}$ is plotted as a function of the speed of the ejecta $w_o$ for (B) and (C), computed including gravitational bending and orbit phase-averaging. At large $w_o$ the kick approaches its maximum limiting value. As shown in the figure, hydrodynamical effects produce a widespread range in velocities, and most remarkably it is able to produce very high kicks, $V_{\text{kick}} \gtrsim 1600 \text{ km s}^{-1}$. 
4. On the bimodal distribution of pulsar kick velocities

The kicks that result from this mechanism are confined to the orbital plane of the evanescent neutron star binary, and thus are likely to be nearly perpendicular to the spin vector of the remnant neutron star, which is probably aligned with the spin of the unstable iron core and the spin of the unstable post-collapse core. A spin-perpendicular kick would be consistent with the requirements imposed by observations of geodetic precession of B1913+16, where the kick is constrained to lie very nearly in the plane of the progenitor binary, which was most likely perpendicular to spins of the spun-up neutron star (i.e. B1913+16) and its pre-explosion companion star (Wex, Kalogera & Kramer 2000; a kick $\gtrsim 250$ km s$^{-1}$ has been invoked for this system).

In contrast, X-ray observations of the Vela pulsar have revealed a jet parallel to its proper motion (Pavlov et al. 2000; Helfand, Gotthelf & Halpern 2001), and it has been argued that the proper motions of both Vela and the Crab pulsar are closely aligned with their spin axes. The kick mechanism studied here would not be able to account for parallel spin and velocity. However, we note that the proper motions of both Vela and the Crab correspond to transverse speeds of $70-141$ km s$^{-1}$ and $171$ km s$^{-1}$ respectively, using reasonable estimates of the distances to the pulsars. For the alignment to be real, the space velocities of these two systems must lie in the plane of the sky. The inferred speeds of these two pulsars are then considerably smaller than the characteristic speed arising from explosion of a low mass, tidally disrupted companion. Plausibly, the birth of Vela and the Crab did not involve an evanescent binary phase; some other mechanism must have been responsible for their spin-aligned kicks (such as those explored by Lai, Chernoff, & Cordes 2001). We are led to suggest that in a pulsar, the larger kick component results from the formation and disruption of short-lived super-close binary, and is perpendicular to the spin axis. The smaller kick component is instead associated with other less vigorous kicks that tend to align with the rotation axis, perhaps because of phase averaging (e.g. Spruit & Phinney 1998). A superposition of these two classes of kicks would also be consistent with the requirement of nearly but not precisely spin-perpendicular kicks to account for the observation of geodetic precession in B1913+16. If this idea is correct, then one expects that the lower velocity neutron stars should have their space velocities predominantly along their spin axes, while the higher velocity neutron stars should have space velocities predominantly perpendicular to their spins. This would create two nearly independent components in the velocity distribution: the “fast” and “very fast” neutron stars. A contamination of low velocity stars belonging to the low velocity “tail” of the high velocity component would come from those explosions in the evanescent binary where light bending and rotational averaging have been more important. This could imply the occurrence of bimodal distribution of velocities for the pulsar population as such inferred from the observations (Arzoumanian, Chernoff, & Cordes 2002). Since the two classes of “fast” and “very fast” pulsars are nearly equally populated, pulsars with large kicks are not exceptional. This would imply that progenitor stars with rapidly rotating iron cores are common in Nature.

5. Black hole kicks

Recently it has been reported that the binary X-ray Nova GRO J1655-40 (Mirabel et al. 2002) hosts the first black hole candidate for which we have evidence of a runaway motion of $112 \pm 18$ km s$^{-1}$ imparted by a natal kick. GRO J1655-40 is a source that shows $\alpha$-elements in its optical spectrum indicating that formation of the black hole was accompanied by a supernova explosion (Israelian et al. 1999). The black hole was very likely born in a two step process in which a hot proto-neutron star forms first, accompanied by the launch of a successful shock wave, but is subsequently destabilized to gravitational collapse by substantial fallback of material from the stellar envelope.

The evanescent binary scenario, proposed here, for the origin of kicks applies natu-
rally to the black hole case, particularly in a fall-back scenario (and not for prompt core collapse). Continuing accretion onto the off-centered spiral pattern could be even more compelling in this case, leading to the formation of a massive fragment, and substantial fall-back on the side where the pattern is not develop fully. Thus, if the formation of a light exploding proto-neutron star accompanies core collapse to a black hole, its maximum kick velocity would scale as \( V_{\text{kick},bh} = V_{\text{kick},\text{ns}}(M_{\text{ns}}/M_{\text{bh}})^{2/3} \). If we hypothesize that both fast black holes and “very fast” pulsars acquire their large speeds via the disruption of an evanescent binary, then we infer fast black hole recoil velocities

\[
    V_{\text{kick},bh} \sim 170 \text{ km s}^{-1} \left( \frac{V_{\text{kick},\text{ns}}}{500 \text{ km s}^{-1}} \right) \left( \frac{M_{\text{ns}}}{1.3M_\odot} \frac{5.4M_\odot}{M_{\text{bh},\text{GROJ1655}}} \right)^{2/3} .
\]

We note that a kick of this magnitude is consistent with the observed value for GRO J1655-40 (Mirabel et al. 2002).

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