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Neutron-Star Birth Kicks

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Abstract. We summarize the evidence for large natal supernova kicks from the observed distribution of pulsar velocities and discuss the difficulties in modelling the intrinsic natal kick distribution. We review the status of the neutron-star retention problem in globular clusters and some of the suggested solutions. We then present evidence from the orbital characteristics of a recently identified separate class of Be X-ray binaries that require neutron stars with very low birth kicks and propose a dichotomous scenario for neutron-star kicks, where neutron stars born in originally relatively close binaries receive small kicks and provide a theoretical framework for such a scenario. Finally, we summarize the main pulsar kick mechanisms that have been proposed and show the results of some of the most recent hydrodynamical core-collapse simulations.

1. Introduction

It is now almost universally accepted that neutron stars receive a substantial kick when they are born, presumably due to an asymmetry in the core collapse or the subsequent supernova explosion, but neither the exact distribution of kick velocities nor the physical origin of these kicks are properly understood. In this contribution, we first summarize the arguments supporting substantial natal kicks and the constraints on the kick-velocity distribution, but then present the case for the need of low-velocity kicks for at least a subset of neutron stars and propose a dichotomous kick scenario. In the last part, we briefly summarize our present theoretical understanding of supernova kicks and present some results from recent core-collapse calculations.

2. The Need for Natal Supernova Kicks

The need for substantial supernova kicks was demonstrated perhaps most convincingly in the study by Lyne & Lorimer (1994), where these authors reassessed the space velocities of young pulsars and showed that the average velocity of young pulsars was $450 \pm 90\,\mathrm{km\,s^{-1}}$, a factor of a few higher than believed previously, mainly due to the adoption of a revised distance model for pulsars.

There is also substantial indirect evidence for large natal kicks. Associations of pulsars with supernova remnants (e.g. Caraveo 1993; Frail et al. 1994) and the displacements of the pulsars from the centers of the remnants imply large kick velocities, sometimes well above $1000\,\mathrm{km\,s^{-1}}$, although it is now clear that some of these associations are chance coincidences. Based on their study of the formation of known double-neutron-star binaries (DNSs), Fryer & Kalogera (1997) concluded that in many of these systems the neutron stars that formed last must have received a natal kick larger than $200\,\mathrm{km\,s^{-1}}$. The large eccentricities of the massive pulsar binaries PSR 1259-63 (Johnston et al. 1992) and PSR J0045-7319 (Kaspi et al. 1994; 1996) are most easily understood if the pulsar received a large kick at birth. In particular in the case of PSR J0045-7319 where the B-star companion has a retrograde spin relative to the orbit, a kick larger than the pre-supernova orbital velocity is required (Brandt & Podsiadlowski 1995). In general, the large eccentricities that are observed in Be/X-ray binaries suggest large kick velocities (Brandt & Podsiadlowski 1995; Verbunt & van den Heuvel 1995; Bildsten et al. 1997). All of this evidence has more-or-less conclusively proven that a large fraction of neutron stars receive natal kicks that are not just associated with the break-up of a binary, the so-called Blauuw-Boersma kick (Blaauw 1961; Boersma 1961).

The understanding of the kick distribution is important since kicks affect the fate of newborn neutron stars in multiple ways (see e.g. Brandt & Podsiadlowski 1995): (1) they determine the space distribution of pulsars and X-ray binaries containing neutron stars, in particular their Galactic scale height; (2) they affect the survival of massive binaries: large natal kicks increase the breakup probability; this may explain the apparently small number of radio pulsars found in binaries, which in turn directly affects the number of DNSs; (3) in contrast, for systems with large mass ratios, supernova kicks can increase the probability for systems to remain bound, in particular in systems which would always break-up without a kick because more than half the total mass of the binary is lost in the supernova; (4) kicks strongly affect the orbital parameters of post-supernova binaries, in particular the eccentricity; and (5) the kick distribution determines the number of neutron stars that can be retained in a globular cluster after the supernova.

3. Modelling the Natal Kick Distribution

Since the original work of Lyne & Lorimer (1994), there have been numerous studies trying to determine the intrinsic natal kick distribution from the observed pulsar data. While Lyne & Lorimer (1994) and Lorimer, Bailes, & Harrison (1997) concluded that the mean pulsar birth velocity was in the range of

450 – 500 $\mathrm{km\,s^{-1}}$ with very few low-velocity pulsars, Hansen & Phinney (1997), studying the same pulsar sample, concluded that the intrinsic distribution was well represented by a Gaussian with a velocity dispersion of 190 $\mathrm{km\,s^{-1}}$ (implying a mean velocity of $\sim 300\,\mathrm{km\,s^{-1}}$), and again containing very few low-velocity pulsars. In contrast, Hartman (1997) using a well-defined sub-sample showed that the data were also consistent with a large population of low-velocity pulsars. Fryer, Burrows, & Benz (1998), who also tried to include other neutron-star constraints, argued for a bimodal kick distribution with a dominant component, including $\sim 70\,\%$ of all neutron stars, receiving kicks larger than 600 $\mathrm{km\,s^{-1}}$, while 30 % of neutron stars receive essentially no kicks. Cordes & Chernoff (1998) also argued in favor of a bimodal Gaussian kick distribution, but with the dominant component, containing 86 % of neutron stars, having a velocity dispersion of 175 $\mathrm{km\,s^{-1}}$ and a smaller component with a velocity dispersion of 700 $\mathrm{km\,s^{-1}}$. In a later related study, Arzoumanian, Chernoff, & Cordes (2002) modified this bimodal distribution to two components with velocities of 90 $\mathrm{km\,s^{-1}}$ and 500 $\mathrm{km\,s^{-1}}$, containing 40 % and 60 % of all systems, respectively.

How is it possible that these different studies, using essentially the same pulsar data, arrive at such different distributions? The problem is that the reconstruction of the intrinsic kick-velocity distribution is extremely model-dependent.

First, there are the *observational selection effects*. There is generally a well-recognized bias in the observed sample against faint (old) pulsars, which needs to be corrected. But there is also a problem of how to include pulsars where there is only an upper limit on the proper motion and the proper-motion errors; this can easily introduce a bias against slow pulsars. Further uncertainties are introduced by the modelling of distance errors and the correction of the asymmetric motion of the pulsar population relative to the Sun, the so-called asymmetric drift.

A second major source of uncertainties arises from the modelling of the *intrinsic pulsar properties*, the radio luminosity function, the shape of the pulsar beam and its variation with spin rate and magnetic field, and the evolution of the magnetic field itself.

The *inclusion of binary effects* introduces further uncertainties due to the uncertainties in the modelling of binary populations in general. The fraction of radio pulsars in binaries provides a strong constraint on the kick distribution, as do the formation rates of X-ray binaries and DNSs, but the latter are not straightforward to include in a kick-distribution analysis. This caveat also applies to the constraints provided by the survival of neutron stars in globular clusters or the constraints from the orbital characteristics of surviving binaries (e.g. the eccentricity distribution).

Another reason for the major differences in the deduced kick distributions arises from the different *modelling approaches*, whether the model uses a forward or backward analysis, a 'complete', but small sample or a statistically corrected larger sample, and the constraints used to model the intrinsic distribution (e.g., whether binary constraints are included or not).

As this discussion illustrates, a complete and thorough re-analysis is urgently needed that uses the much larger and much better defined pulsar sample that has recently become available (D.R. Lorimer 2004, private communication).

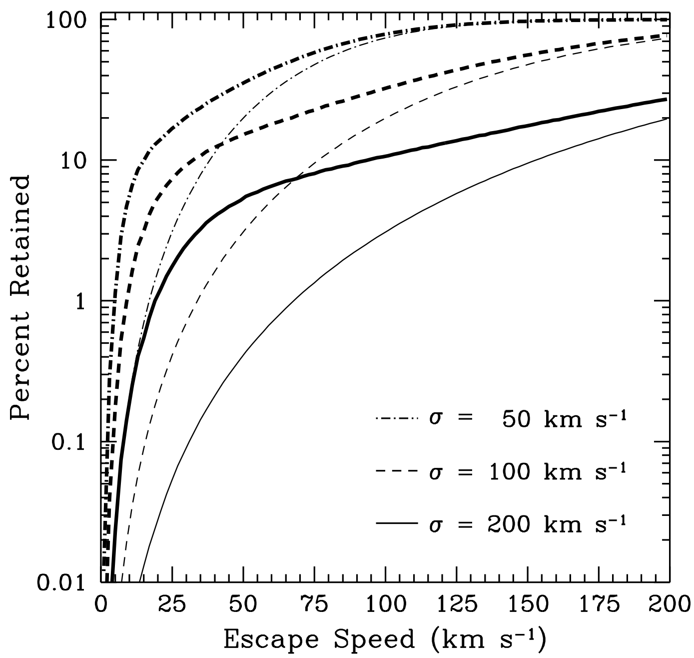

Figure 1. Percentage of neutron stars retained in a globular cluster as a function of the cluster escape speed, for a Maxwellian distribution of kick speed. Thick curves correspond to binary channels, while thin curves are for single stars only. (From Pfahl et al. 2002a.)

4. The Neutron-Star Retention Problem

There is good observational and theoretical evidence that some of the massive globular clusters in our Galaxy contain more than ~ 1000 neutron stars (10–20 % of all neutron stars formed in a cluster). However, the presence of even as few as ~ 100 neutron stars is difficult to reconcile with any kick distribution that does not have a substantial low-velocity ($< 50\,\mathrm{km\,s^{-1}}$) component. The thin curves in Figure 1 show the neutron-star retention fractions as a function of cluster escape velocity for different Maxwellian kick distributions. They show that for most clusters (with escape speeds less than $50\,\mathrm{km\,s^{-1}}$), at most a few % of neutron stars can be retained, if the kick distribution has a velocity dispersion $> 100\,\mathrm{km\,s^{-1}}$. This is known as the neutron-star retention problem (for a detailed review and references see Pfahl, Rappaport, & Podsiadlowski 2002a).

One of the proposed solutions to this problem (Brandt & Podsiadlowski 1995) is based on the fact that neutron stars formed in massive binaries are much easier to retain, since the kick momentum given to the neutron star is shared with a massive companion, leading to a much lower systemic velocity for the post-supernova binary. The solid curves in Figure 1 show the resulting retention fractions when these effects are included. For a typical cluster like 47 Tuc, some 6 % of neutron stars can now be retained, significantly improving the situation.

Drukier (1996) concluded that the inclusion of massive binaries could solve the retention problem, but only if globular clusters were initially more massive (with an initial mass of $\sim 10^7\,M_\odot$). Ivanova & Rasio (in this volume) show that it is possible to reproduce most of the observed neutron-star systems in 47 Tuc with a standard kick distribution, using an initial fraction of primordial binaries close to 100 %.

While these results suggest that the retention problem is much less severe if massive binaries are included, an alternative solution is a separate population of neutron stars with low birth kicks.

5. A Dichotomous Kick Scenario

The best evidence at present that some neutron stars only receive small kicks comes from the orbital properties of a class of massive, wide Be X-ray binaries with very low eccentricities, where X Per with an orbital period of 250 d and eccentricity of 0.1 provides the prototype (Pfahl et al. 2002b). The orbits of these systems are sufficiently wide that tidal circularization is negligible, so that the observed eccentricities should reflect the conditions immediately after the SN explosion. Such low eccentricities essentially require that the neutron stars in these systems received low kick speeds of $\lesssim 50\,\mathrm{km\,s^{-1}}$.

Pfahl et al. (2002b) and Podsiadlowski et al. (2004) suggested that this behavior can be understood if the kick distribution is dichotomous. Podsiadlowski et al. (2004) speculated that close binaries, where the secondary loses its envelope before helium core burning, produce neutron stars with low kicks, arguing that the evolution of the core of a massive star is very different if it evolves in a close binary rather than in a wide binary or as a single star.

Stars with initial masses larger than $\sim 11\,M_\odot$ that experience core collapse will generally have smaller iron cores at the point of explosion if they lost their envelopes due to a binary interaction during or soon after core hydrogen burning. Stars below $\sim 11 M_\odot$, on the other hand, can end up with larger helium and metal cores if they have a close companion, since the second dredge-up phase which reduces the helium core mass dramatically in single stars does not occur once the hydrogen envelope is lost (see Fig. 2). Stars in binary systems with masses in the range $8 - 11\,M_\odot$ are likely to undergo an electron-capture supernova, while single stars in the same mass range would end as ONeMg white dwarfs. Since the compact cores are much smaller in this case, it is much easier to eject the envelope (i.e., produce a successful supernova) in this case. This is likely to lead to a prompt or fast explosion, where the instabilities that cause large kicks do not have time to develop. This naturally produces neutron stars with low-velocity kicks, in contrast to a very slow, delayed neutrino-driven explosion, which are likely to produce a 'standard' large kick.

Figure 4 illustrates this dichotomous kick scenario and Figure 5 shows the distribution of orbital period and eccentricity for a binary population synthesis simulation based on this dichotomous kick scenario, where some of the observed systems are also indicated. In these simulations we assumed that all stars with initial masses between 8 and $14\,M_\odot$ received a small kick (with a mean kick

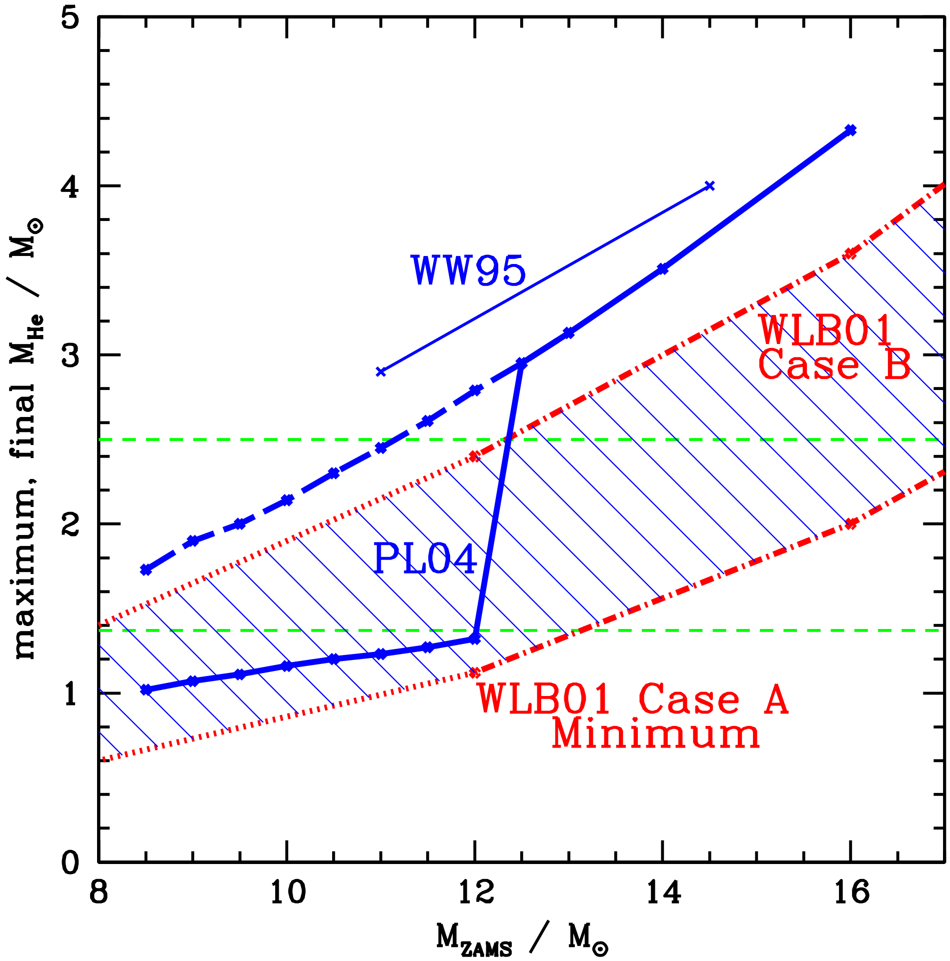

Figure 2. Final mass (thick solid line) and maximum mass (thick dashed line) of the helium core in single stars as a function of initial mass according to Poelarends & Langer (2004) (PL04). For comparison, the final helium core masses from the calculations of Woosley & Weaver (1995) are indicated by a thin solid line. The final helium core masses of close binary models undergoing Case B mass transfer from Wellstein, Langer & Braun (2001, WLB01) are shown as the upper dot-dashed line, while those experiencing Case A mass transfer (WLB01) may lie anywhere between the lower dot-dashed line and the Case B line. The results from the binary calculations have been extrapolated for initial masses below 12 $M_\odot$ (dotted part). Note that the PL04 and WLB01 models have been computed with the same assumptions for convective mixing, while the WW95 models assumed a higher semiconvective mixing efficiency. 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. (From Podsiadlowski et al. 2004.)

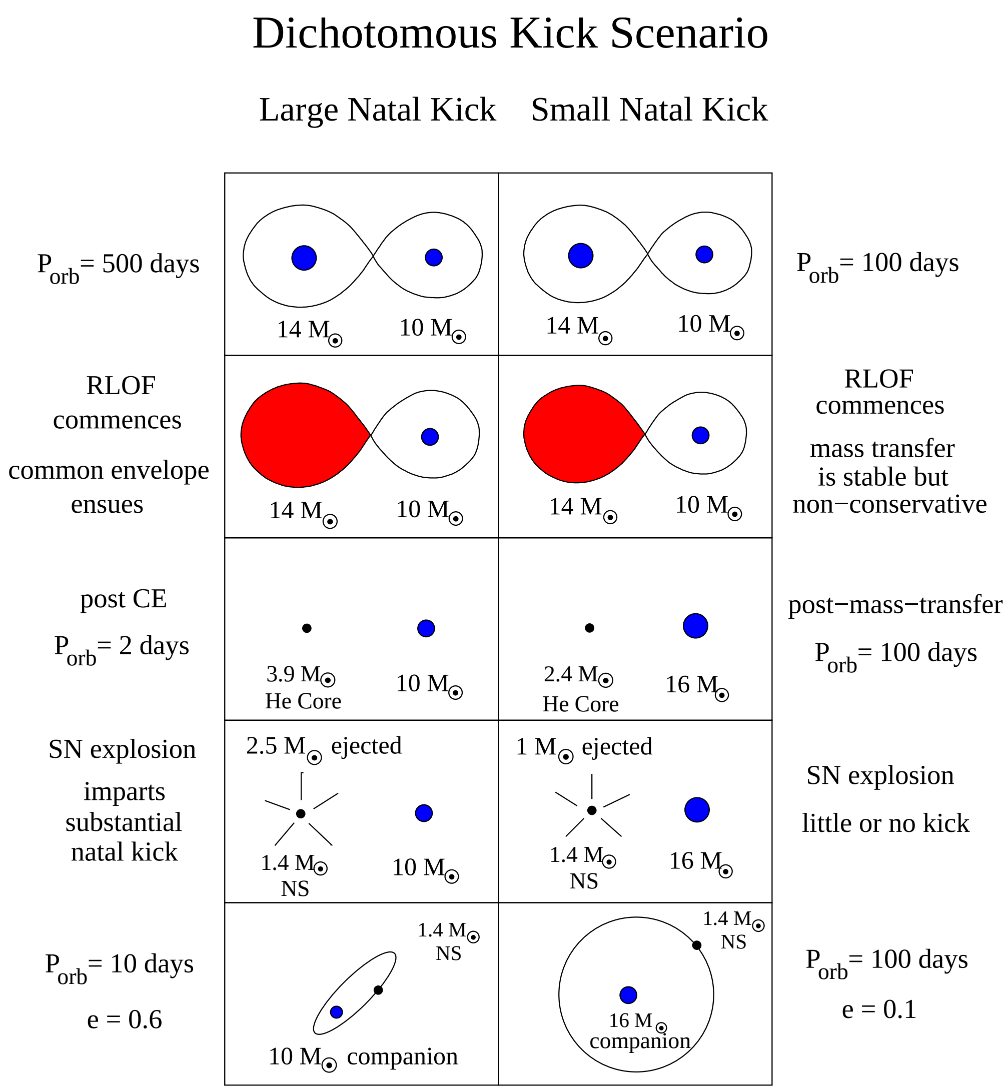

Figure 3. Illustrative binary evolution scenarios leading to the formation of high-mass X-ray binaries. In the left panel, the binary is sufficiently wide at the onset of mass transfer that the primary has a fully formed 3.9 $M_\odot$ He core. By contrast, in the right panel the primary's envelope is lost while the He core is substantially lower in mass (2.4 $M_\odot$). In the proposed dichotomous kick scenario the former case leads to a large natal kick, while the latter case results in a "prompt (fast)" supernova event and a smaller kick. (From Podsiadlowski et al. 2004.)

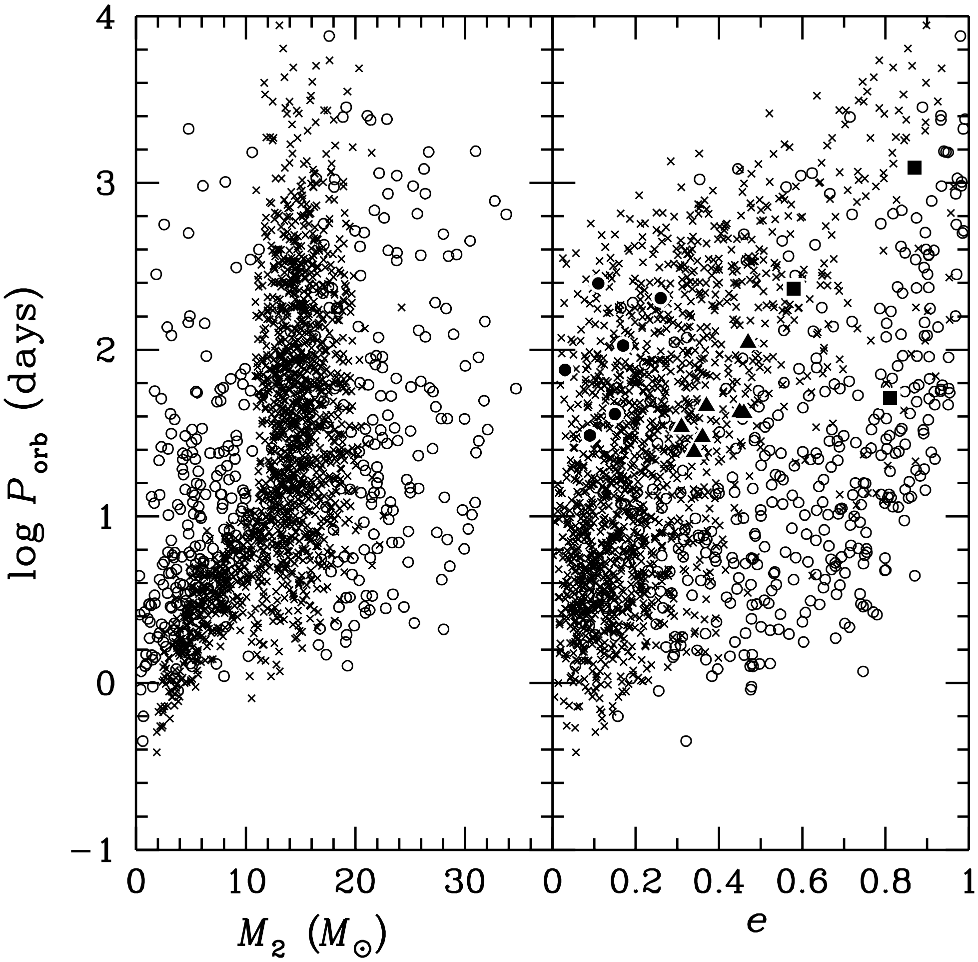

Figure 4. Results of a single HMXB binary population synthesis calculation that utilizes our proposed dichotomous kick scenario. Each circle (cross) represents a system where the primary was (was not) highly evolved when it lost its hydrogen-rich envelope, and the exposed core evolved to collapse to form a neutron star with a subsequent large, conventional (small, unconventional) natal kick; see the text for details. Markers in the right panel indicate the observed wide, low-eccentricity HMXBs (*filled circles*), and the well-known eccentric HMXBs (*filled triangles*). The *filled squares* show the three radio pulsars with massive binary companions in eccentric orbits. We did not include observed systems with $P_{\rm orb} \lesssim 10$ days, since their orbital parameters are likely to have been altered by tidal circularization effects. (From Podsiadlowski et al. 2004.)

velocity of $30\,\mathrm{km\,s^{-1}}$) if mass transfer began before the ignition of helium in the core and a large kick (with a mean of $300\,\mathrm{km\,s^{-1}}$) in all other cases to simulate the final core-mass behavior illustrated in Figure 1.

6. Pulsar Kick Mechanisms

Quite a number of pulsar kick mechanisms have been proposed in the past. These can be sub-divided into pre-natal, natal and post-natal kick mechanisms.

In the *pre-natal kick* scenario, pulsars form from runaway OB stars that result from binary breakup (Gott, Gunn, & Ostriker 1970). In the *post-natal kick* scenario, a pulsar with an off-center magnetic dipole is accelerated *after* the supernova due to an electromagnetic rocket effect (Harrison & Tademaru 1975; Lai, Chernoff, & Cordes 2001).

In a *natal kick* scenario, a kick can be caused by the asymmetric collapse of the core, where the asymmetries are due to asymmetric mass ejection and/or asymmetric neutrino emission.

If the magnetic field in a proto-neutron star is high ($> 10^{15}\,\mathrm{G}$), kicks can be driven by the *magnetic effects on the neutrino emission*, either due to the dependence of the neutrino scattering/absorption opacities on magnetic fields, producing kicks $v_{\mathrm{kick}} \sim 50\,\mathrm{km\,s^{-1}}\,(B/10^{15}\,\mathrm{G})$ (Arras & Lai 1999) or magnetic accretion that produces neutrino dark spots (Thompson & Duncan 1996).

Hydrodynamical mechanisms are some of the better studied mechanisms. Burrows & Hayes (1996) proposed that kicks could be caused by asymmetries in the pre-supernova structure that causes asymmetric collapse. Such asymmetries could, for example, be due to overstable g modes in these cores (Goldreich, Lai, & Sahrling 1996; Lai & Goldreich 2000) or asymmetries in the O-Si burning shell of the progenitor (Bazan & Arnett 1998). Fryer (2004) has modelled the collapse of such asymmetric cores, but found that he needed a very large (excessively large?) initial perturbation ($> 25\,\%$) and a fast explosion to get kicks larger than $\sim 500\,\mathrm{km\,s^{-1}}$.

In a perhaps more promising hydrodynamical kick mechanism, the kick is caused by convection-driven instabilities ($l = 1, 2$ modes). In the recent simulations by Scheck et al. (2004), a large supernova kick (up to and above $500\,\mathrm{km\,s^{-1}}$) is caused by asymmetries in the neutrino flux, which have their origin in low-order instabilities driven by the convective motion behind the stalled shock. An essential requirement in these simulations, which allows these convective instabilities to grow, is that the duration of the convective, stalled phase is longer than $\sim 500\,\mathrm{ms}$ (i.e., many convective turnover timescales). Such *slow* explosions are expected for fairly large iron cores. In contrast, for a small iron cores or in the case of electron-capture supernovae, the simulations by Scheck et al. (2004) suggest *fast* explosions where these convectively driven instabilities are unable to grow, leading to rather small kick velocities. These simulations in particular provide some theoretical support for the dichotomous kick scenario discussed earlier.

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