Part 1

Neutron Star Formation and Evolution

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Neutron Star Formation and Birth Properties

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Abstract. Our current knowledge of neutron star formation, progenitors, and natal masses, spins, magnetic fields, and space velocities is briefly reviewed from a theorist's perspective. More observational information is badly needed to constrain theoretical possibilities.

1. Introduction: The Beginning Matters

Although only a wink in its life, the moment of birth of a neutron star marks a spectacular astrophysical event with far-reaching consequences. Neutron stars originate from the apocalyptic death of massive stars in supernova (SN) explosions. While Baade & Zwicky (1934) first came up with this visionary suggestion, the link is now unambiguously established by associations of pulsars and compact X-ray sources with young gaseous SN remnants, e.g. in the famous cases of the Crab pulsar and Crab nebula, Vela pulsar and nebula, or the Cassiopeia A remnant with the compact central object that was pinpointed with high resolution by the *Chandra* X-ray Observatory.

Neutron stars are certainly among the most exotic known objects. With the size of roughly three gravitational radii they contain more than a solar mass of matter at a density exceeding that in atomic nuclei. The gravitationally bound object is kept in mechanical equilibrium by repulsive interactions and degeneracy pressure of nucleons that balance the enormous pull of gravity. The extreme compactness allows pulsars to rotate with periods as low as a millisecond and to possess surface magnetic fields up to 15 orders of magnitude higher than that of the Earth. Extraordinary conditions like these make them unique astrophysical laboratories for nuclear physics, particle physics, and gravitational physics.

The birth of a neutron star constitutes the transition of matter on a macroscopic scale to the most extreme state realized after the big bang. The throes are signaled by the conversion of huge amounts of gravitational binding energy mostly to neutrinos (up to $\sim$99% or several 10^{53} ergs), some to kinetic energy of the explosion ejecta or wind loss ($\sim$1%), and minor parts to electromagnetic radiation ($\sim 10^{49}$ ergs) and gravitational waves ($\sim 10^{46}$ ergs, possibly more). These forms of energy release suggest potential observability, but the rate of nearby SNe is low and available empirical data are sparse. Much of our knowledge of neutron star formation and birth properties like mass distribution, spins, magnetic fields, proper motions, is therefore based on theoretical work, which, however, is hampered by the complexity of the problem and barely constrained

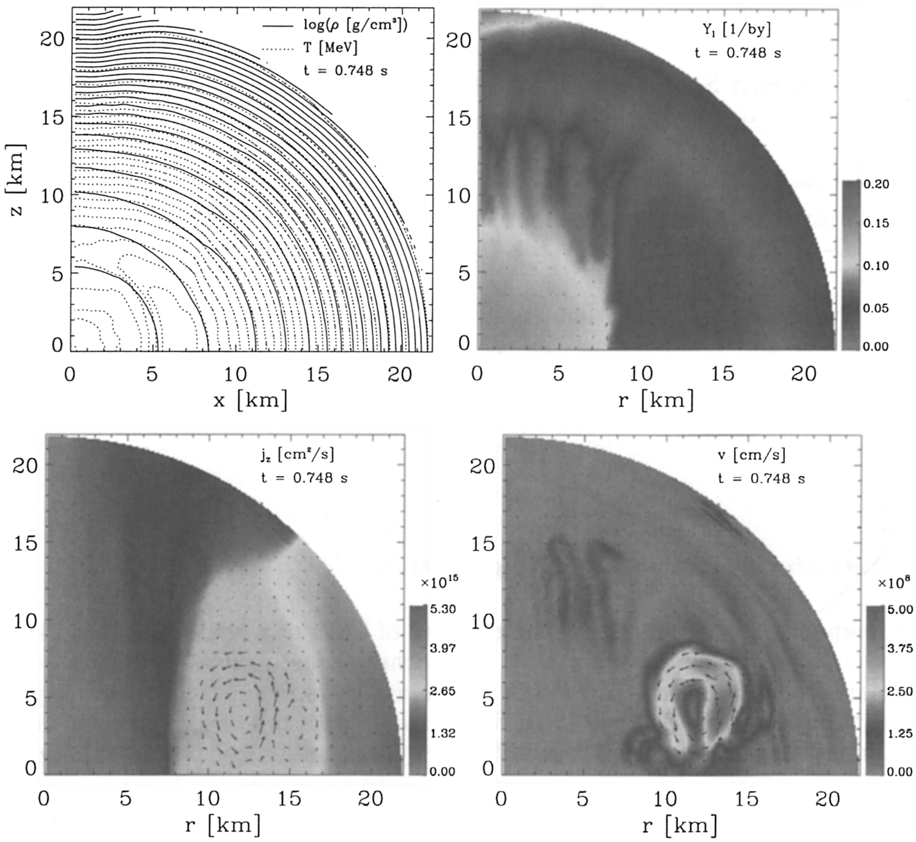

Figure 1. Meridional cuts through a differentially rotating, convective nascent neutron star 0.75 seconds after its formation. The rotation axis coincides with the ordinates of the plots. In a quasi-steady state, convection is strongest at intermediate radii in a region of essentially constant specific angular momentum near the equator. It is only weakly developed closer to the rotation axis where elongated, convective cells occur that are aligned parallel to the axis. A steep gradient of the specific angular momentum suppresses convective motion perpendicular to the axis in this region. In contrast, in a non-rotating star convective activity takes place in a spherical shell. The hydrodynamic simulation was carried out with neutrino diffusion taken into account (Keil 1997; Janka & Keil 1998; Janka et al. 2001). *Top left:* Contours of constant density (solid lines) between $3.67 \times 10^{10}\,\mathrm{g\,cm^{-3}}$ and $2.68 \times 10^{14}\,\mathrm{g\,cm^{-3}}$, increasing with a factor of 1.37, and of constant temperature (dotted lines) between 4 MeV and 30 MeV with steps of 1 MeV. *Top right:* Lepton fraction Y_l (density of electrons plus electron neutrinos minus their antiparticles relative to the number density of nucleons). *Bottom left:* Specific angular momentum j_z; the rotation period is ~1 ms at 3 km distance from the rotation (z) axis, ~2.5 ms at 10 km and ~6 ms at 20 km. *Bottom right:* Total velocity in radial and lateral directions. The arrows indicate the flow direction in a meridional plane.

degrees of freedom, e.g. in the initial conditions or input physics for models. A brief moment in evolution therefore poses a big challenge for exploration.

2. Unveiling the Invisible: Signals from Birth

Neutron stars are born as hot objects which initially contain a large number of electrons, electron neutrinos and protons. They lose their lepton content, neutronize, and cool by the emission of neutrinos on a timescale of several tens of seconds (Burrows & Lattimer 1986; Keil & Janka 1995; Pons et al. 1999). The neutrino burst from this phase was detected in the case of supernova 1987A in the form of two dozen events by three underground experiments, which thus opened the door to extragalactic neutrino astronomy. The measurement of such a neutrino burst from a Galactic supernova with present experimental facilities could yield tens of thousands of counts (e.g., Dighe, Keil & Raffelt 2003), providing us with important information about the supernova dynamics and neutron star equation of state (e.g., Pons et al. 2001).

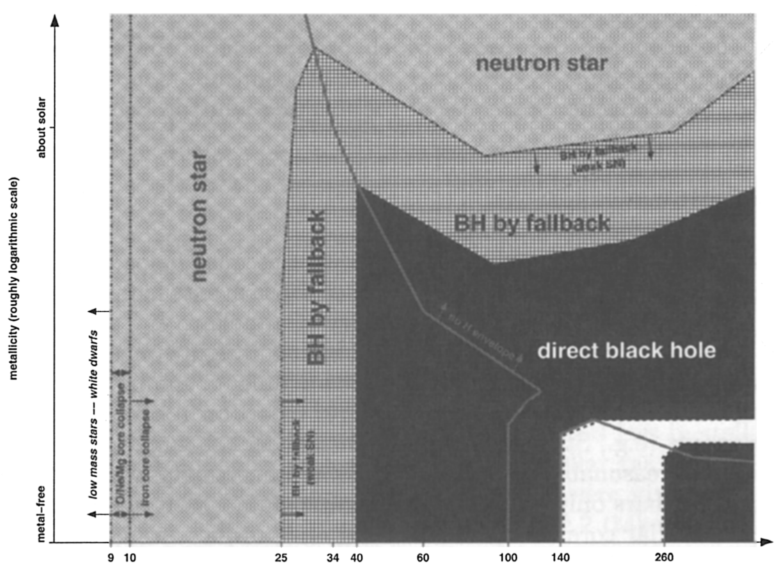

Figure 2. Remnants of massive single (nonrotating) stars as a function of initial metallicity. The evolution of a star depends on its mass loss, which increases for more massive stars and for higher content of metals in the stellar plasma. This explains the downward slope of the thick solid line above which the stars lose their hydrogen envelope. In the white strip near the right lower corner pair-instability supernovae leave no compact remnant, in the white region on the left side low-mass stars end their lives as white dwarfs (Fig. from Heger et al. 2003).

Similarly exciting would be the detection of gravitational waves, which can be produced at the moment of core bounce and by long-time post-bounce pulsations and oscillations, "r-mode instability", or convective activity in the interior

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of the newly formed compact remnant (e.g., Müller et al. 2004). Immediately after stellar core collapse the nascent neutron star develops convection in a region below the neutrinosphere (e.g., Buras et al. 2003), driven mainly by a negative gradient of the lepton fraction, i.e, of the number of leptons per baryon (Epstein 1979). This convective region digs deeper into the neutron star and encompasses an increasingly thicker spherical shell as time advances. Two-dimensional hydrodynamic simulations including neutrino diffusion (Keil 1997; Keil, Janka & Müller 1996) were able to follow the evolution of the contracting, convective proto-neutron star over a period of more than one second and confirmed the picture suggested by stability analysis of spherically symmetric models (Burrows 1987; Miralles, Pons & Urpin 2000). Self-consistent simulations with rotation showed that the angular momentum transport by convection quickly (within only $\sim$100 ms) leads to a quasi-steady state with highly differential rotation in which convection is strong near the equatorial plane but suppressed near the poles and close to the rotation axis. This suppression is caused by the stabilizing effect of a steep increase of the specific angular momentum j_z with distance from the axis in the corresponding region (Fig. 1; Janka & Keil 1998; Janka, Kifonidis & Rampp 2001).

How frequent are the events which produce such powerful neutrino and gravitational wave signals? What are their progenitors? And what can be said about the characteristic properties of the forming neutron stars?

3. Progenitors

Recent counts of SN rates in galaxies of different morphological types suggest that Type II and Ib,c SNe from stellar core-collapse events happen in our Galaxy (Sb-Sbc) with a rate of 1.5 ± 1.0 per century (Cappellaro & Turatto 2001; Cappellaro, Evans & Turatto 1999). This means that roughly once every $\sim$65 years a compact remnant — a neutron star or black hole — should be formed. This estimate is a factor of two lower than values based on recorded historical SNe or SN remnants (e.g., Strom 1994), but considering the large uncertainties both numbers are in reasonable agreement. Another uncertainty, which, however, enlarges the error bars only insignificantly, is associated with the unknown rate of faint events, stellar core collapses which do not produce bright supernovae and thus could only be discovered by neutrino or gravitational wave measurements.

Accretion induced collapse (AIC) of white dwarfs in binaries, which was invoked to explain large populations of millisecond pulsars in globular clusters (Grindlay & Bailyn 1988), is likely to contribute only at a minor level. Fryer et al. (1999) constrained the possible rate of such dim neutron star formation events by observed Galactic element abundances, which limit the integral amount of ejected neutron-rich matter and associated production of particular isotopes (e.g., ^{62}Ni, ^{66}Zn, ^{68}Zn, ^{87}Rb, and ^{88}Sr). From their collapse models they deduced an allowed event rate of typically a few $\sim 10^{-5}$ per year and at most several $\sim 10^{-4}$ per year. This is two to three orders of magnitude lower than the stellar core collapse rate (see also Woosley & Baron 1992) and in rough agreement with the AIC rate needed to account for millisecond pulsars in globular clusters (Bailyn & Grindlay 1990). This agreement of both limits, however, may be purely accidental, because the amount of n-rich ejecta could be much smaller than predicted by the simulations. It is sensitive to the neutron and proton interactions of ν_e and $\bar{\nu}_e$ that are radiated from the newly formed neutron star. The relevant physics is described only rather approximately in the existing simulations.

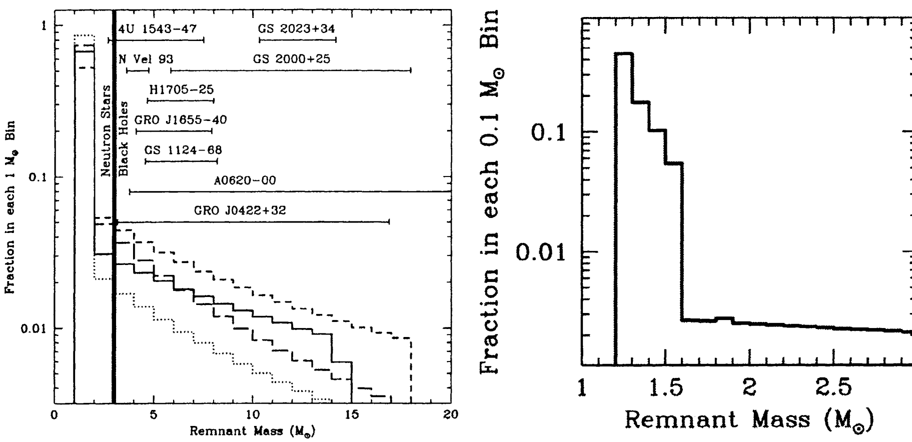

Figure 3. *Left panel:* Mass distribution of compact remnants predicted from supernova simulations by Fryer. The different curves use different stellar initial mass functions and different estimates of the amount of fall back in the explosion. 60–80% of the compact remnants are neutron stars if black holes are formed above $\sim 3\,M_\odot$. *Right panel:* Calculated distribution of neutron-star remnant masses. Both figures are taken from Fryer & Kalogera (2001).

Stellar core collapse can lead to the formation of a neutron star or a black hole, depending on the initial mass and mass loss of the star during its evolution, both of which determine the core mass before collapse. Moreover, the initial metallicity of the star has crucial influence, since the mass loss in stellar winds is sensitive to the opacity and thus metallicity of the stellar gas. Recent reviews of the evolution of single stars and their final stages were given by Heger et al. (2003) and Woosley, Heger & Weaver (2002). Figure 2 (taken from Heger et al. 2003) shows that for solar metallicity neutron stars are expected to emerge from stars above $\sim 9\,M_\odot$ and below about $25\,M_\odot$. Above this mass black holes form either by fall back of matter which is unable to become unbound in the supernova explosion or directly if the stellar core is too massive to allow for the launch of an outward moving supernova shock. Fryer (1999) determines the limit for direct black hole formation to be around $40\,M_\odot$ and for black hole formation by fall back to be somewhere between $18\,M_\odot$ and $25\,M_\odot$. The uncertainty of the latter limit is associated with the progenitor structure in this stellar mass range and with yet unresolved problems of the core-collapse physics which prohibit definite predictions of the supernova explosion energy. Above about $33\,M_\odot$ the stars lose their whole hydrogen envelope before collapse and become Wolf-Rayet stars with strong mass loss (Woosley et al. 2002). For a sufficiently high mass loss during this phase a "window" may exist above $\sim 50\,M_\odot$ where again neutron stars are formed (Fig. 1).

4. Masses

Theoretical neutron star and black hole mass distributions were determined through supernova simulations by Fryer & Kalogera (2001). Figure 3, which is taken from this paper, shows that neutron stars are dominantly produced in the mass range 1.2–1.6 $M_\odot$, above which the distribution of compact remnant masses falls off exponentially. With an adoped maximum neutron star mass of $\sim$3 $M_\odot$ about 80% of the compact remnants are neutron stars. The results show some variation with different assumptions about the initial mass function of progenitors, supernova energies, initial mass of the protoneutron star, and amount of fall back, as well as binary effects.

A close comparison with measured neutron star masses is also hampered by the small number of accurate mass measurements on the one hand and the unclear exact relation between (observable) gravitational masses and (computed) baryonic masses on the other. This mass relation depends on the properties of the high-density equation of state which determines the mass to radius ratio and the binding energy of the neutron star. But current theoretical analysis at least does not reveal any obvious inconsistency with known masses of neutron stars (Thorsett & Chakrabarty 1999) and black hole candidates (Bailyn et al. 1998).

The nature of the compact remnant in supernova 1987A is still unclear. The detection of two dozen neutrinos from SN 1987A was an unambiguous signal of the formation of a protoneutron star. This star, however, could have become gravitationally unstable after seconds of neutrino cooling, either triggered by the accretion of fall back matter (e.g., Brown, Bruenn & Wheeler 1992) or by a gradual softening of the supranuclear equation of state due to phase transitions (e.g., Brown & Bethe 1994; Keil & Janka 1995; Glendenning 1995). The existence of a black hole in SN 1987A is therefore not excluded, but there is also no compelling argument in favor of this possibility. If the neutron star has either a low magnetic field or a low rotational frequency, it could well remain invisible (Fryer, Colgate & Pinto 1999) just like the faint compact object in Cas A has been until a few years ago.

5. Spins and Magnetic Fields

Little is known about the rotation rates and magnetic fields of newly born neutron stars. Only recently has stellar evolution theory begun to include the transport of angular momentum in models which attempt to follow massive star evolution up to core collapse (e.g., Heger et al. 2004).

Massive stars are seen to rotate rapidly at the surface, but their core properties need to be determined by numerical calculations. During stellar evolution angular momentum is lost through mass outflow in winds, and transported from the interior by convection, shear, circulation, and magnetic torques.

Stars that start their evolution on the zero-age main sequence with characteristic equatorial rotation velocities $\sim$200 km s^{-1} at the surface (corresponding to about 10% of the break-up velocity) retain a specific angular momentum of some 10^{16} cm^2 s^{-1} prior to collapse. This is so large that neutron stars spinning with sub-millisecond periods would emerge. Such rotation near the critical limit is associated with a huge rotational energy (several 10^{52} ergs) which would be set free when the neutron star is decelerated to measured periods of young pulsars ($\gtrsim 10\,$ms; Marshall et al. 1998). There is no observational evidence of any such gigantic energy release from ordinary supernovae. On the other hand, specific angular momenta in excess of $10^{16}\,\mathrm{cm}^2\,\mathrm{s}^{-1}$ just outside the core are needed for progenitors of gamma-ray bursts (e.g., Woosley & Heger 2004).

Including the effects of magnetic torques during stellar evolution reduces the core angular momentum by a factor of ~ 20, suggesting the formation of young neutron stars with periods of several milliseconds (Heger et al. 2004). This appears to be in reasonable agreement with observational constraints, although some slowing by neutrino-powered magnetic winds in the case of magnetar-strength ($\sim 10^{15}$G) ordered surface fields (Thompson, Chang & Quataert 2004), the propeller mechanism in case of fall back of slowly moving supernova ejecta, or the pulsar radiation mechanism, might take place during the first seconds, days, or years, respectively, of the neutron star's life (Woosley & Heger 2004).

Pre-collapse magnetic fields are estimated to be around $5 \times 10^9\,$G for the toroidal component and of order $10^6\,$G for the radial part (Heger et al. 2004). The field strength can increase during core collapse by a factor of $\sim$1000. Further field amplification on timescales of hundreds of milliseconds to seconds could occur due to differential rotation by the magneto-rotational instability (Akiyama et al. 2003), field winding (e.g., Müller & Hillebrandt 1979), or due to convection by dynamo action (Thompson & Duncan 1993). Realistic and quantitatively meaningful simulations have still to be done.

It is pointed out here that neutrinos, although carrying away a fair fraction of the rest-mass energy of the forming neutron star ($\sim 0.16\,\mathrm{M}_\odot c^2 (M_\mathrm{ns}/1.4\,\mathrm{M}_\odot)^2 = 0.12\,M_\mathrm{ns} c^2 (M_\mathrm{ns}/1.4\,\mathrm{M}_\odot)^2$; Lattimer & Prakash 2001), are rather inefficient in removing angular momentum. The total angular momentum, J_ns, changes when the (gravitational) mass of the neutron star is reduced by neutrino emission according to (Epstein 1978; Baumgarte & Shapiro 1998):

$$\frac{\dot{J}_\mathrm{ns}}{J_\mathrm{ns}} = q\,\frac{f(\lambda)}{\kappa_n}\,\frac{\dot{M}_\mathrm{ns}}{M_\mathrm{ns}}\,, \tag{1}$$

where q is an efficiency parameter ($q = 0$ if the neutrinos are emitted from the center, $q = 1$ for homogeneous volume emission without scattering, $q = 5/3$ for the diffusion case). The function $f(\lambda)$ accounts for the deformation of the rotating star and depends on the ratio of polar to equatorial radius, $\lambda = (R_\mathrm{p}/R_\mathrm{e})^2$. Assuming ellipsoidal shape, it is $f(\lambda) = 0.60(1+4\lambda)/(1+2\lambda)$. Note that the angular momentum loss relative to the energy loss decreases when the object becomes more oblate: $f = 1$ for $\lambda = 1$ whereas $f = 0.6$ for $\lambda = 0$. The factor κ_n is a dimensionless structure constant of order unity which depends on the density profile of the star. For a polytropic equation of state, $P = K\rho^{1+1/n}$, κ_n can be derived from the Lane-Emden function, which gives, e.g., $\kappa_n = 1$ for $n = 0$, $\kappa_n = 0.81482$ for $n = 0.5$, $\kappa_n = 0.65345$ for $n = 1$ (cf. Table 1 in Lai, Rasio & Shapiro 1993). Taking $qf(\lambda)/\kappa_n \approx$ constant during the cooling and contraction of the neutron star, Eq. (1) can easily be integrated to yield the ratio of final to initial quantities:

$$\frac{J^\mathrm{f}_\mathrm{ns}}{J^\mathrm{i}_\mathrm{ns}} = \left(\frac{M^\mathrm{f}_\mathrm{ns}}{M^\mathrm{i}_\mathrm{ns}}\right)^{qf(\lambda)/\kappa_n}\,. \tag{2}$$

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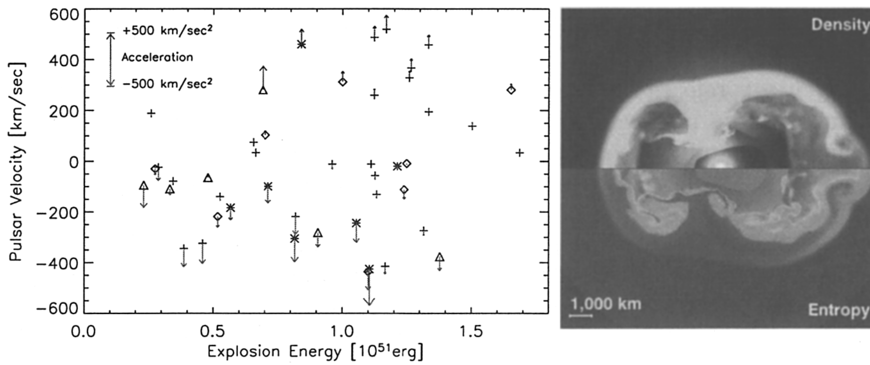

Figure 4. *Left panel:* Kick velocities of pulsars vs. SN energy after one second of shock evolution as obtained in a sample of about 50 simulations. The length of the arrows indicates the size of the continuing acceleration at one second post bounce when the simulations were stopped. Positive and negative values correspond to pulsar kicks in both directions of the symmetry axis of the two-dimensional models (Scheck et al. 2004). The pulsar receives the opposite momentum of the explosion ejecta which can develop large global asymmetry due to the non-linear growth of hydrodynamic instabilities in the neutrino-heating region between neutron star and shock. *Right panel:* One of the models, one second after stellar core collapse. Density (top) and entropy distribution are shown. The explosion has an energy of 1.4×10^{51} ergs and is stronger towards the right. The neutron star (invisible at the center) correspondingly receives a recoil velocity of 380 km/s to the left.

Pushing all involved numbers to their extrema, i.e., $q = 5/3$, $1/\kappa_n = 1.53$, $f(\lambda) = 1$, and $M_{\rm ns}^{\rm f}/M_{\rm ns}^{\rm i} = 0.8$, we get $J_{\rm ns}^{\rm f}/J_{\rm ns}^{\rm i} = 0.57$ and for the specific angular momenta, $j = J/M$: $j_{\rm ns}^{\rm f}/j_{\rm ns}^{\rm i} = 0.71$. This means that neutrinos can remove at most 43% of the total angular momentum and thus reduce the specific angular momentum by ∼30% relative to its initial value.

6. Pulsar Kicks

Young neutron stars are observed to possess average space velocities of 200–500 $\mathrm{km\,s^{-1}}$ (Lyne & Lorimer 1994), a significant fraction might move even faster than 1000 $\mathrm{km\,s^{-1}}$ (Arzoumanian, Chernoff & Cordes 2002). These velocities are most likely imparted to the neutron star by a kick associated with its birth. Binary breakup is not sufficient to account for the measured velocities. An intrinsic acceleration is also required to explain special properties of neutron star binaries (for reviews, see Lai, Chernoff & Cordes 2001 and Lai 2001).

Suggested mechanisms for natal neutron stars kicks can be grouped into two categories: either they ascribe pulsar velocities to anisotropies of the SN explosion or they attribute them to the recoil associated with anisotropic neutrino emission during the neutrino cooling phase. A global asymmetry of the radiated neutrinos of only ∼3% yields $v_{\rm ns} \approx 1000\,\mathrm{km\,s^{-1}}(E_\nu/3{\times}10^{53}\mathrm{ergs})(M_{\rm ns}/1.4\,\mathrm{M_\odot})^{-1}$.

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However, producing asymmetries in the protoneutron star interior which are sufficiently large to account for even only 1% emission anisotropy turns out to be extremely difficult and requires ultra-strong magnetic fields ($\sim 10^{16}$G) and/or speculative assumptions about neutrino properties (e.g., Lai et al. 2001).

There exists, on the other hand, firm observational evidence for large asymmetries in supernovae (e.g., inferred from visible deformation of the ejecta or polarization measurements), and there is general agreement that hydrodynamic instabilities lead to large-scale overturn and mixing behind the supernova shock already during the very early moments of the explosion (e.g., Janka et al. 2004). Recently it was shown by simulations that such instabilities can produce global explosion asymmetries by which a net impulse of more than 500 km s^{-1} can be transferred to the neutron star on a timescale of one second or longer (Fig. 4; Scheck et al. 2004; see also Thompson 2000). Alternatively, inhomogeneities in the core of the evolved star might grow during core collapse (Lai 2001 and references therein) and might cause an anisotropic shock breakout and large pulsar recoil (Burrows & Hayes 1996; but see Fryer 2004). If statistical hints of a two-component velocity distribution of radio pulsar data (e.g., Arzoumanian et al. 2002) bear truth (and not just have the trivial meaning that more free parameters allow for better fits), different mechanisms may be at work in subsets of the neutron star population.

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