

HYDRODYNAMICAL NEUTRON STAR KICKS IN THREE DIMENSIONS

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ABSTRACT

Using three-dimensional (3D) simulations of neutrino-powered supernova explosions we show that the hydrodynamical kick scenario proposed by Scheck et al. on the basis of two-dimensional (2D) models can yield large neutron star (NS) recoil velocities also in 3D. Although the shock stays relatively spherical, standing accretion-shock and convective instabilities lead to a globally asymmetric mass and energy distribution in the postshock layer. An anisotropic momentum distribution of the ejecta is built up only after the explosion sets in. Total momentum conservation implies the acceleration of the NS on a timescale of 1–3 seconds, mediated mainly by long-lasting, asymmetric accretion downdrafts and the anisotropic gravitational pull of large inhomogeneities in the ejecta. In a limited set of $15 M_{\odot}$ models with an explosion energy of about 10^{51} erg this stochastic mechanism is found to produce kicks from $<100 \text{ km s}^{-1}$ to $\gtrsim 500 \text{ km s}^{-1}$, and $\gtrsim 1000 \text{ km s}^{-1}$ seem possible. Strong rotational flows around the accreting NS do not develop in our collapsing, non-rotating progenitors. The NS spins therefore remain low with estimated periods of $\sim 500\text{--}1000$ ms and no alignment with the kicks.

Subject headings: supernovae: general — pulsars: general — stars: neutron — stars: kinematics and dynamics

1. INTRODUCTION

Young neutron stars (NSs) possess average space velocities around 400 km s^{-1} , much larger than those of their progenitor stars, implying that they are accelerated during the birth in a supernova (SN) explosion (e.g., Faucher-Giguère & Kaspi 2006; Hobbs et al. 2005; Arzoumanian et al. 2002). Moreover, alignment of the NS spin and kick was inferred for the Crab and Vela pulsars (Kaplan et al. 2008; Ng & Romani 2007) and several other young pulsars (see Wang et al. 2006, and references therein) from comparisons of the direction of proper motion with the projected rotation axis as determined from the symmetry axis of the pulsar wind nebula on X-ray images. The same conclusion was drawn for samples of radio pulsars from the linear polarization of the pulses, whose position angle reflects the spin direction (Johnston et al. 2005; Rankin 2007). However, the Crab and Vela pulsars may not be good cases for determining misalignments because they are moving at smaller speeds than the average pulsar population and therefore the unknown velocity of the progenitor implies a bigger uncertainty. On the other hand, also the radio data do not seem to make a clear case for a general alignment of spin and kick directions in the reference frame of the progenitor’s motion (Johnston et al. 2007).

Analysing the observational information, also of characteristics of NS binaries, Lai et al. (2001) concluded that the NSs received their kicks most probably at the time of the SN explosion. A large variety of mechanisms for natal kicks has been proposed, either by hydrodynamical effects linked to large-scale asymmetries of the SN explosion (e.g., Herant 1995; Burrows & Hayes 1996; Janka & Müller 1994; Thompson 2000; Scheck et al. 2004, 2006) or by anisotropic neutrino emission from the nascent NS (e.g., Chugai 1984; Burrows & Woosley 1986; Socrates et al. 2005). However, it is very difficult to produce even only a one-percent global dipole asymmetry of the neutrino emission, which is needed for a kick of 300 km s^{-1} . For this to be possible one has to invoke controversial assumptions like very strong global dipolar magnetic fields inside the NS ($\gtrsim 10^{16}$ G; e.g., Arras & Lai

1999), arguable neutrino properties (e.g., sterile neutrinos, large neutrino magnetic moments; e.g., Fuller et al. 2003), or unsettled mechanisms to create strong emission asymmetries in the neutrinospheric region (e.g., Socrates et al. 2005).

On the basis of 2D SN models Scheck et al. (2004, 2006) argued that the standing accretion shock instability (SASI; Blondin et al. 2003; Foglizzo & Tagger 2000; Foglizzo 2002), which grows after shock stagnation and causes large global non-radial asymmetry of the accretion flow to the NS and of the beginning SN explosion, can lead to kicks of typically several hundred km s^{-1} and even more than 1000 km s^{-1} if the dipole ($\ell = 1$) component of the asymmetry was sufficiently strong. Blondin & Mezzacappa (2007) showed in idealized, stationary-accretion setups that SASI spiral modes may also have the potential to generate pulsar spin periods consistent with observations. In this *Letter* we present the first simulations of SN explosions from core bounce to ~ 1.5 s later that confirm the potential of SASI-induced asymmetries to produce typical NS kicks in the more realistic 3D environment of collapsing stellar cores.

2. NUMERICAL SETUP

We use the explicit finite-volume, Eulerian, multi-fluid hydrodynamics code PROMETHEUS (Fryxell et al. 1991; Müller et al. 1991a,b). The advection of nuclear species is treated by the Consistent Multi-fluid Advection (CMA) scheme of Plewa & Müller (1999), and self-gravity according to Müller & Steinmetz (1995). General relativistic corrections of the monopole are taken into account as in Scheck et al. (2006) and Arcones et al. (2007).

All simulations are computed on an axis-free overlapping “Yin-Yang” grid (Kageyama & Sato 2004) in spherical polar coordinates, which was recently implemented into our code (Wongwathanarat et al. 2010). We use $400(r) \times 47(\theta) \times 137(\phi) \times 2$ grid cells corresponding to an angular resolution of 2° and covering the full 4π solid angle. Better resolution in the inner region of our computational domain is achieved by a constant radial zone size of about 0.030 km up to $r \approx 100 \text{ km}$. The radial grid is logarithmically spaced beyond this radius

TABLE 1
EXPLOSION AND NS PROPERTIES FOR ALL MODELS AT 1.4 s AFTER BOUNCE.

Model	M_{ns} [M_{\odot}]	t_{exp} [ms]	E_{exp} [B]	v_{ns} [km/s]	a_{ns} [km/s^2]	$J_{\text{ns},46}$ [$\text{g cm}^2/\text{s}$]	α_{sk} [$^{\circ}$]	T_{spin} [ms]
W15-1	1.37	246	1.12	331	175	1.51	117	652
W15-2	1.37	248	1.13	405	144	1.56	58	632
L15-1	1.58	421	1.13	161	66	1.89	148	604
L15-2	1.51	381	1.74	78	3	1.04	62	1041

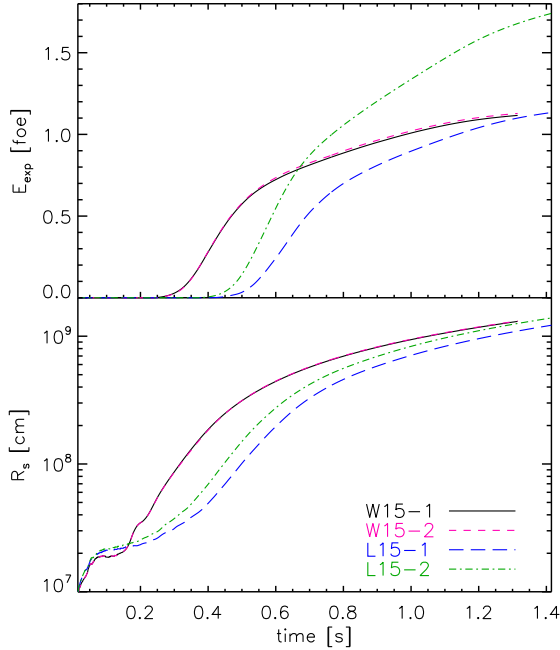


FIG. 1.— Time evolution of the SN explosion energy E_{exp} (top) and of the average shock radius R_s for all computed models. Since models W15-1 and W15-2 differ only in the initial random seed perturbations of the radial velocity field, the results for these models are essentially identical and the short-dashed and solid lines lie on top of each other. Despite the similarity of the global parameters, both models develop different explosion asymmetries and neutron star kicks (see Table 1 and Fig. 2).

up to an outer grid boundary of $R_{\text{ob}} = 18000 \text{ km}$, which is sufficient to prevent the SN shock from leaving the computational domain during the simulated time. At R_{ob} a free outflow boundary is chosen.

The high-density inner core of the proto-NS (PNS) is excised and replaced by a point mass at the coordinate origin. The shrinking of the PNS is mimicked by a retraction of the closed inner boundary at R_{ib} together with the radial grid. Hydrostatic equilibrium is assumed at R_{ib} . The stellar fluid is described by the tabulated microphysical equation of state (EoS) of Janka & Müller (1996). Neutrino transport and neutrino-matter interactions are approximated as in Scheck et al. (2006) by radial integration of the one-dimensional (spherical), grey transport equation for all angular grid directions (θ, ϕ) independently. This “ray-by-ray” approach allows for angular variations of the neutrino fluxes.

3. INVESTIGATED MODELS

Our models W15 and L15 are based on two non-rotating $15 M_{\odot}$ progenitors, s15s7b2 of Woosley & Weaver (1995) and a star evolved by Limongi et al. (2000), which were followed through collapse to 15 ms after bounce with the PROMETHEUS-VERTEX code in one dimension (R. Buras and A. Marek, pri-

vate communication). To break spherical symmetry, random seed perturbations of 0.1% are imposed on the radial velocity (v_r) field. Explosions with chosen energy are initiated by neutrino heating depending on suitable values of the neutrino luminosities imposed at the lower boundary.

Our models W15-1 and W15-2 differ only by the initial seed perturbations, while L15-2 is set to have a higher explosion energy than L15-1. Table 1 lists the corresponding explosion energies E_{exp} at $\sim 1.4 \text{ s}$ p.b. and explosion times t_{exp} defined as the instant when E_{exp} (i.e., the total energy of all zones where the internal plus kinetic plus gravitational energy is > 0) is 10^{48} erg . Figure 1 shows that this moment coincides roughly with the time when the average SN shock radius, R_s , exceeds 500 km. The W15 models explode earlier and their NS (baryonic) mass, M_{ns} (defined as enclosed mass at a radius R_{ns} where the density is $10^{11} \text{ g cm}^{-3}$), is therefore smaller.

4. NEUTRON STAR KICKS AND SPINS

Neutrino heating around the NS triggers delayed explosions, which are preceded (and supported) by a postbounce phase of several 100 ms of violent SASI and convective activity. This leads to large-scale asymmetries of the ejecta, potentially imposing a kick and spin to the NS, for which we evaluate our simulations in a post-processing step. The time evolution of the NS kick velocity v_{ns} , NS angular momentum J_{ns} , lateral and longitudinal angles of the kick direction (θ_{kick} and ϕ_{kick} , respectively), and the angle α_{sk} between spin and kick directions are plotted in Fig. 2. The final numbers are given in Table 1 (J_{ns} values there are normalized by 10^{46}), supplemented by the NS acceleration a_{ns} at the end of the runs and our estimated NS spin periods T_{spin} .

Since the NS is excised and replaced by a point mass at the grid center, it cannot travel. Nevertheless, like a wall reflecting a bouncing ball, it can absorb momentum (but will not move as if it had an infinite inertial mass). Because of total linear momentum conservation in the rest frame of the progenitor, we can (following Scheck et al. 2006) compute \mathbf{v}_{ns} from the negative of the total momentum \mathbf{P}_{gas} of the gas outside of the NS as

$$\mathbf{v}_{\text{ns}}(t) = -\mathbf{P}_{\text{gas}}(t)/M_{\text{ns}}(t), \quad (1)$$

where $\mathbf{P}_{\text{gas}} = \int_{R_{\text{ns}}}^{R_{\text{ob}}} dV \rho \mathbf{v}$. Tests confirmed very good linear momentum conservation of our code, while angular momentum is more difficult to conserve, e.g., when a rotating gas mass is in rapid motion across large distances on the grid. We therefore estimate \mathbf{J}_{ns} again as the negative of the angular momentum of the exterior gas, but by integrating only over the volume between R_{ns} and $r_o = 500 \text{ km}$ and adding to this the angular momentum that is carried by the gas flux leaving this sphere:

$$\mathbf{J}_{\text{ns}}(t) = -\left(\int_{R_{\text{ns}}}^{r_o} dV \rho \mathbf{j}(t) + A_o \int_0^t dt' (\rho \mathbf{j} v_r) |_{r_o} \right), \quad (2)$$

where \mathbf{j} is the specific angular momentum and $A_o = 4\pi r_o^2$. This assumes that the asymmetric gas mass outside of r_o does not exert any important torque on the gas mass below r_o . Accordingly, we see $\mathbf{J}_{\text{ns}}(t)$ asymptoting (see Fig. 2) when accretion on the NS ends (around 0.6–0.8 s after bounce). At this time the asymmetric downdrafts of cool gas filling the volumes between rising bubbles of high-entropy, neutrino-heated matter (Fig. 3, left and right panels) do not reach down below 500 km, but are replaced by the spherically symmetric

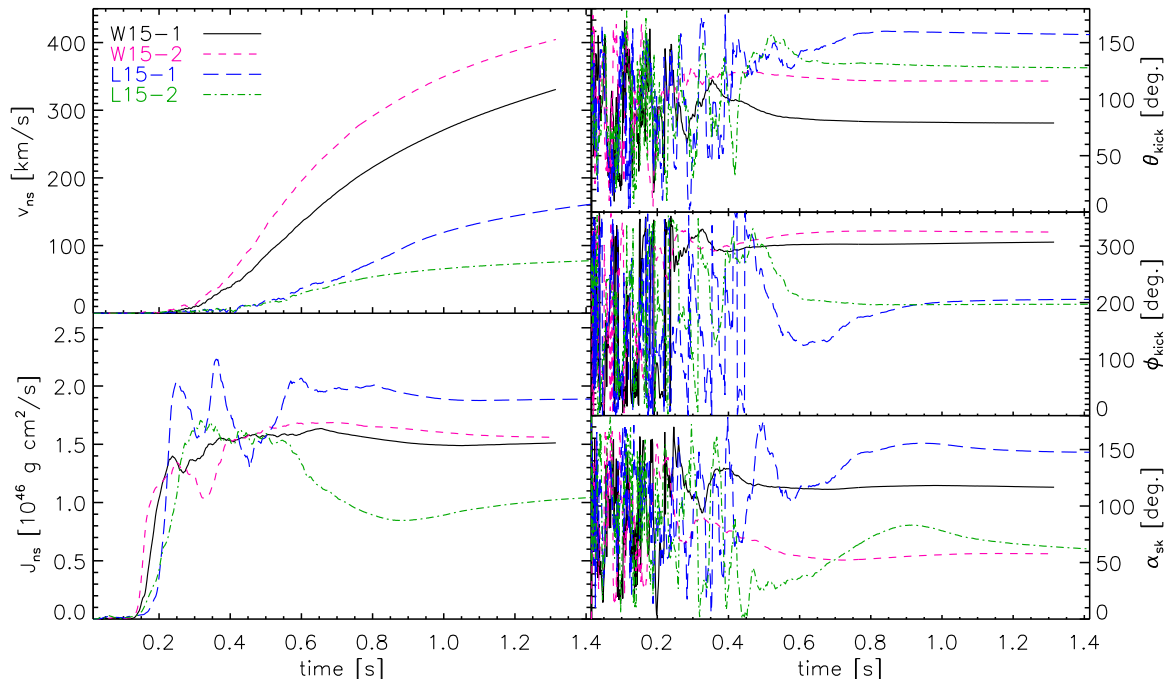


FIG. 2.— Time evolution of NS velocity v_{ns} (top-left), angular momentum J_{ns} (bottom-left), latitudinal (top-right) and azimuthal (middle-right) angles of the NS kick vector, θ_{kick} and ϕ_{kick} , respectively, and the angle α_{sk} between the NS spin and kick directions (bottom-right).

neutrino-driven wind around the NS (green region in the right panel of Fig. 3). Assuming $J_{\text{ns}} = |\mathbf{J}_{\text{ns}}|$ is const after the end of our simulations (at $t \approx 1.4$ s p.b.), we obtain a rough estimate of the final NS spin period from $T_{\text{spin}} = 2\pi I_{\text{ns}}/J_{\text{ns}}$ by considering a rigidly rotating, homogeneous sphere of mass M_{ns} , i.e., $I_{\text{ns}} = \frac{2}{5}M_{\text{ns}}R_{\text{ns}}^2$, with a final radius of $R_{\text{ns}} = 12$ km.

We find NS kick velocities between 80 km s^{-1} (L15-2) and 405 km s^{-1} (W15-2). In the latter case the acceleration at 1.3 s p.b. is still about 150 km s^{-2} (Table 1). Assuming that half of this value applies for another second leads to a final kick of nearly 500 km s^{-1} . Comparing Figs. 1 and 2 one sees that the kick remains very small ($\lesssim 10 \text{ km s}^{-1}$) and the kick direction fluctuates chaotically in all cases before the explosion takes off. Only after the radial expansion of the ejecta sets in and the asymmetry pattern of energy and density distribution gets frozen in, the NS acceleration takes place and continues for 1–3 seconds (Scheck et al. 2006). Accordingly, the kick finds its final direction only shortly afterwards (at 0.4–0.5 s in W15-1 and W15-2 and 0.6–0.8 s in L15-1 and L15-2).

Decomposing the radial integral $D(\theta, \phi) = \int_{R_{\text{ns}}}^{R_{\text{s}}} dr \rho(r)$ in spherical harmonics with the polar axis chosen aligned with the kick vector, we find that the $\ell = 1$ mode clearly dominates after 0.3–0.4 s p.b. in W15-1 and W15-2, the models with the largest kick, while this effect is absent in the low-kick models L15-1 and L15-2. In Fig. 3, middle panel, the dipolar asymmetry of the explosion is clearly visible. The NS recoil (white arrow) is opposite to the direction of the fastest shock expansion (towards the upper left) driven by big high-entropy bubbles. The lower density there is contrasted by much higher density and slower gas expansion in the opposite direction. Accordingly, the geometrical center of the shock and ejecta shell is displaced from the grid center (and NS location) by several 1000 km (see middle and right panels of Fig. 3).

Besides kicks the PNSs attain angular momentum ($1\text{--}2 \times 10^{46} \text{ g cm}^2 \text{ s}^{-1}$) without any obvious correlation in magnitude and direction to the recoil. We estimate final NS spin

periods between 600 ms and 1000 ms (Table 1). Evaluating $D(\theta, \phi)$ for spherical harmonics with the axis parallel to the spin vector, an $\ell = 1, m = 1$ mode appears as the dominant non-axisymmetric mode in the W15-models after 0.4 s p.b., reflecting the mass imbalance on both sides of the spin vector as directly visible for W15-2 in the middle panel of Fig. 3.

5. PHYSICAL ORIGIN OF THE NS KICKS AND SPINS

The described hydrodynamic NS acceleration proceeds in three stages. (1) Initially convective mass flows and SASI sloshing motion of the postshock layer create an anisotropy of the mass-energy distribution around the PNS. Convective downdrafts, channelling gas accreted through the stalled shock into the neutrino-heating region, get deflected to feed an asymmetric pattern of high-entropy bubbles. The energy-loaded bubbles are created, collapse again, and reappear in a quasi-chaotic way to become smaller or larger, absorbing less or more neutrino energy. This stochastic bubble formation, however, does not cause an appreciable recoil of the NS (Fig. 2). (2) When the explosion sets in, the shock and postshock gas begin to expand aspherically, driven by the asymmetric inflation of the bubbles. The ejecta gas therefore gains radial momentum and its c.o.m. begins to shift away from the coordinate origin (Fig. 3): The ejecta shell acquires a net linear momentum because of different strengths of the explosion in different directions. The initial *energy and mass asymmetry* is thus converted to a *momentum asymmetry* by the conversion of thermal to kinetic energy through hydrodynamical forces. When the expansion timescale becomes shorter than the timescale of lateral mixing, the asymmetric ejecta structures freeze in. (3) Because of linear momentum conservation, the NS must receive the negative of the total momentum of the anisotropically expanding ejecta mass. Hydrodynamic pressure forces alone cannot achieve the NS acceleration (Scheck et al. 2006). As long as accretion downdrafts reach the NS, momentum is transferred by asymmetric gas flows. Stronger accretion on the weaker side of the

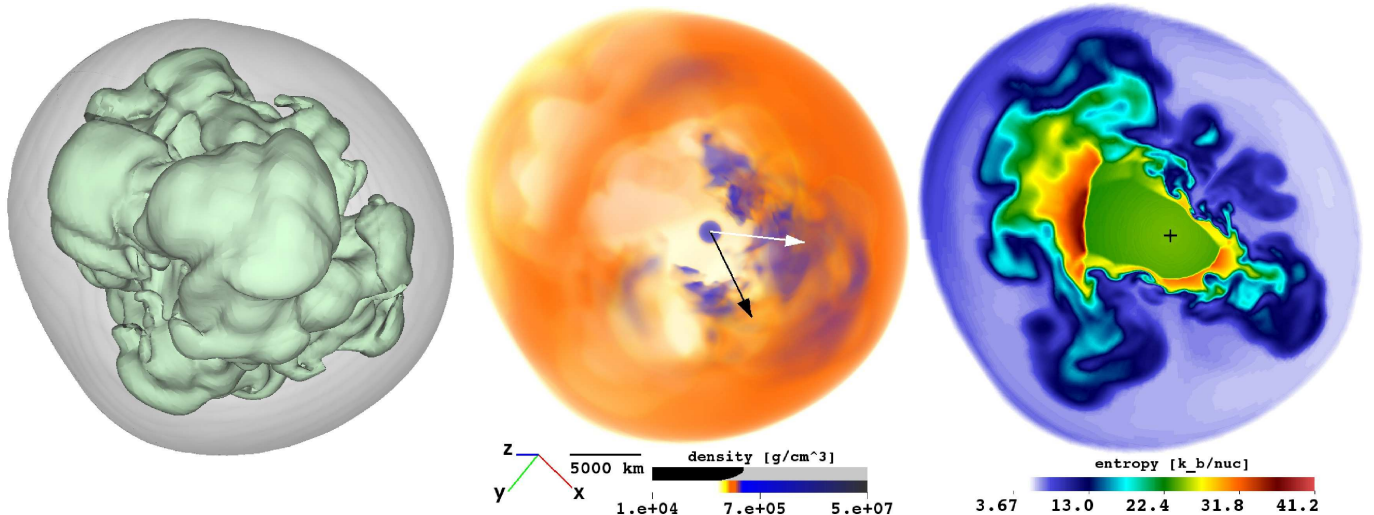


FIG. 3.— Entropy-isosurfaces of the SN shock and the high-entropy bubbles (*left*), ray-casting image of the density (*middle*), and entropy distribution in a cross-sectional plane through the center (*right*) at $t = 1.3$ s after bounce for model W15-2. The outer boundaries coincide with the shock surface, the viewing direction is normal to the plane of the NS kick and spin vectors, which also define the plane for the entropy slice. The kick and spin directions are indicated by the white and black arrows, respectively, in the *middle figure*. The NS location is also marked by a black cross in the *right plot* and is clearly displaced from the geometrical center of the expanding shock. The SN shock has an average radius of 13000 km (a length of 5000 km is given by a yardstick below the *middle image*) but shows a pronounced dipolar deformation, which is clearly visible from the color asymmetry of the postshock gas between the lower right (weaker shock with minimum radius of 11000 km) and upper left (stronger shock with maximum radius of 15000 km) directions. The *middle plot* corresponds roughly to the projection of the density distribution on the observational plane. Dilute bubble regions are light-colored in white and yellow, while dense clumps appear more intense in reddish and bluish hues. The blue circle around the NS represents the dense inner region of the spherically symmetric neutrino-driven wind. This wind is visible in green in the *right image* and is bounded by the aspherical wind termination shock. The wind is shocked to higher entropies on the left side, where it passes the termination shock at larger radii because of the faster expansion of the preceding SN ejecta.

blast and more mass loss in the neutrino-driven wind on the other side cause a recoil opposite to the main explosion direction. However, the largest (time-integrated) kick contribution, which continues even after accretion has ended and the wind has become spherical (Fig. 2), results from the gravitational pull of the anisotropic shell of ejecta (Scheck et al. 2006). A hemispheric asymmetry of the mass distribution of $\Delta m = \pm 10^{-3} M_{\odot}$ in a shell expanding away from the NS from a radius $r_i = 100$ km with $v_s = 1000$ km s $^{-1}$ can drag it to a velocity of $v_{\text{NS}} \approx 2G\Delta m/(r_i v_s) \approx 2700$ km s $^{-1}$. Ejecta asymmetries can thus effectively mediate a long-lasting pull on the NS.

We do not expect any significant contribution to the NS kick by anisotropic neutrino emission, because most of the neutrino energy is radiated from the spherical neutrinospheric layer (Scheck et al. 2006). Moreover, including the NS motion is unlikely to change our results, at least statistically for a larger sample of models. This was concluded by Scheck et al. (2006) from tests in which the gas surrounding the NS in the grid center was allowed to move with $(-v_{\text{NS}})$ by applying a Galilei transformation. The displacement of the NS is small compared to the asymmetry scale of the ejecta that cause a gravitational acceleration of the NS over seconds. Scheck et al. (2006) also observed little influence of the NS motion on the neutrino emission asymmetry and its associated (very small) NS recoil, in contrast to findings by Fryer (2004).

Our 3D simulations were followed much longer beyond the onset of the explosion than previous 3D studies by Fryer (2004) and Fryer & Young (2007). This is *essential because the hydrodynamical NS kicks are no impulsive pre-explosion effect* (as, e.g., assumed by Janka & Müller 1994) *but a long-time post-explosion phenomenon*. The global asymmetry of the mass-energy distribution in the postshock gas created before the explosion mainly by SASI activity (as analysed in

detail by Scheck et al. (2008) for the considered SN core conditions) is converted to a momentum asymmetry of the ejecta and the NS only gradually after the initiation of the blast. Since the acceleration continues for seconds, kicks of ≥ 500 km s $^{-1}$ are possible although an extreme dipolar shock deformation and persistent one-sided accretion as seen in some 2D models of Scheck et al. (2006) are absent in the presented 3D results.

The NS spin grows considerably faster than the kick but saturates also earlier (Fig. 2). Angular momentum is transferred to the NS by off-center impacts of the anisotropic accretion downdrafts (Burrows et al. 1995; Spruit & Phinney 1998). When the accretion ends, the exterior gas separates from the compact remnant. Different from mediating an acceleration by their gravitational drag, the anisotropic ejecta then cannot exert any torque on a spherical, point-like compact remnant. Therefore the NS spins remain fairly slow, because in spite of an $\ell = 1$, $m = 1$ density asymmetry we do not find the strong, ordered rotational gas flows near the accreting PNS as seen by Blondin & Mezzacappa (2007). Possibly the investigated SN core conditions are not favorable for the growth of rotating spiral modes (see, e.g., Fernández 2010) or their growth timescale is longer than the explosion timescales in our models.

6. CONCLUSIONS

Our 3D results support the NS recoil scenario proposed on the basis of 2D models by Scheck et al. (2004, 2006). The still small set of 3D simulations for two $15 M_{\odot}$ stars yields kicks between ~ 50 km s $^{-1}$ and ~ 500 km s $^{-1}$ in the range of the measured space velocities of young pulsars. Since even for our most extreme model the explosion asymmetry of the SN is still fairly small, NS acceleration well beyond 500 km s $^{-1}$ seems possible. But since the kick mechanism is a quasi-chaotic and stochastic phenomenon, rare cases with more than

1000 km s⁻¹ as in 2D (Scheck et al. 2006) will require many more model runs, varying the initial random seed perturbations as well as the stellar progenitor and explosion energy.

This will also be necessary for statistically significant conclusions on the relative orientations of NS spins and kicks. Considering nonrotating stars we find spin periods of ~500–1000 ms, but do not see reasons for a spin-kick alignment. For a closer assessment of this question, however, also the investigation of progenitors with rotation is necessary. Core rotation due to the angular momentum of the progenitor (or established by a first strong thrust) might impose a predefined direction and lead to rotational averaging of the following NS acceleration so that a preferentially aligned spin-kick distribution emerges instead of random distributions of

the direction vectors (Wang et al. 2007, 2006; Ng & Romani 2007). Moreover, even a modest amount of angular momentum can lead to higher growth rates of corotating, non-axisymmetric SASI (spiral) modes with potentially important consequences for NS spins and kicks (Blondin & Mezzacappa 2007; Yamasaki & Foglizzo 2008).

The recoil scenario described here and by Scheck et al. (2004, 2006) predicts the NS escaping opposite to the direction of the maximum explosion strength. We thus suspect that the nickel production of the SN and the iron concentration in the SN remnant could be higher in the hemisphere pointing away from the NS motion.

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