Supernova Asymmetries and Pulsar Kicks — Views on Controversial Issues

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Abstract. Two- and three-dimensional simulations demonstrate that hydrodynamic instabilities can lead to low-mode ($l = 1, 2$) asymmetries of the fluid flow in the neutrino-heated layer behind the supernova shock. This provides a natural explanation for aspherical mass ejection and for pulsar recoil velocities even in excess of 1000 km/s. We propose that the bimodality of the pulsar velocity distribution might be a consequence of a dominant $l = 1$ mode in case of the fast component, while higher-mode anisotropy characterizes the postshock flow and SN ejecta during the birth of the slow neutron stars. We argue that the observed large asymmetries of supernovae and the measured high velocities of young pulsars therefore do not imply rapid rotation of the iron core of the progenitor star, nor do they require strong magnetic fields to play a crucial role in the explosion. Anisotropic neutrino emission from accretion contributes to the neutron star acceleration on a minor level, and pulsar kicks do not make a good case for non-standard neutrino physics in the nascent neutron star.

1. Introduction

In the past years much work has been devoted to start exploration of the very wide and certainly interesting parameter space associated with rapid rotation and, linked to it, with the growth of strong magnetic fields in stellar core collapse and supernova (SN) explosions. These studies have different motivation. Some of them aim at computing templates of gravitational-wave signals for the now operational interferometer experiments (e.g., Dimmelmeier, Font, & Müller 2002a,b; Ott et al. 2004; Kotake, Yamada, & Sato 2003a). Some of them intend to study the differences between neutrino-driven SN explosions of non-rotating progenitors and only recently available pre-collapse models with rotation (e.g., Fryer & Heger 2000, Fryer & Warren 2004, Kotake, Yamada, & Sato 2003b). Others are undertaken to support the idea that magnetic fields provide the driving force of massive star explosions and could generate MHD jets in SNe (e.g., Akiyama et al. 2003; Thompson, Quataert, & Burrows 2004, Kotake et al. 2004, Obergaulinger 2004), a hypothesis which is inspired by the discovery of gamma-ray burst jets from collapsing stars, by polarization measurements and observed asymmetries of SNe, and by the growing evidence of highly-magnetised neutron stars (NSs), the magnetars.

Rotation of the stellar iron core is considered here as "rapid" if it noticably affects gravitational collapse, core bounce, and early post-bounce evolution of the SN. This requires *pre-collapse* rotation rates of significantly more than $1\,\mathrm{rad\,s^{-1}}$ in the stellar center; SN modelers typically assume values of 3–$10\,\mathrm{rad\,s^{-1}}$ or more to study rotational effects during core collapse. A NS with 10 km final radius will spin with a period around 1 ms if it forms from an iron core that rotates rigidly with only $\sim 0.5\,\mathrm{rad\,s^{-1}}$, provided angular momentum is conserved during the formation process. Rapid differential rotation after collapse must also be expected to strongly amplify even small initial seed fields by winding or by the magneto-rotational instability, in which case magnetic field effects could certainly not be ignored in discussions of the explosion mechanism.

But what is the theoretical and observational basis for the assumption that SN cores are in "rapid" rotation, that rotation determines the geometry of the explosion, and that strong magnetic fields are a crucial ingredient for understanding the start of the explosion? Are rapid rotation and magnetic fields needed to solve the long-standing problem how massive stars explode, and to explain why SNe are deformed and why pulsars have large velocities? In the following we shall argue that there is currently no solid ground for such claims.

NS spin periods at birth, e.g. of the Crab pulsar, are estimated to be longer than 10–20 ms (in some cases hundreds of ms), provided the deceleration can be calculated backward in time by using the magnetic dipole model. NSs like the ones in SN 1987A or in Cassiopeia A rotate at much less than the Crab rate, or must have a very weak surface field. In both cases there is no trace of the energy output from a bright, Crab-like pulsar. The compact X-ray source at the center of Cas A is four orders of magnitude fainter than Crab, and again there is no sign of the energy output from the spin-down of an initially very fast rotator. So there is no direct information for rapid rotation of the SN *core* in the gaseous remnants of both explosions. Although the ring system of SN 1987A confirms large angular momentum in the outer layers of the exploded star — possibly due to a binary merger event some 10,000 years before the explosion took place (Podsiadlowski 1992; Podsiadlowski, Joss, & Rappaport 1990) — this does not mean that the SN core at collapse had rotated rapidly. The apparent prolate deformation of the ejecta of SN 1987A, which has been interpreted as a signature of rapid rotation with an axis perpendicular to the plane of the inner, bright ring, should be taken with caution. Dust formation is likely to have an important influence on the observational appearance of the ejected gas (McCray 2004). The sizable polarization of the light of many SNe and, in particular, the growth of the polarization with time and thus with deeper view into the more and more transparent ejecta, are also no unambiguous evidence that strong rotation is the origin of the underlying deformation. *Any* physical process which triggers the explosion in a largely aspherical way and imposes a global directionality on the mass ejection will also produce polarization that grows towards the center. Wispy filaments in the outer parts of the Cas A remnant are looked at as relics of a "jet" and a "counter-jet", but these structures are Si and not Fe rich (Hwang et al. 2004). If linked to the center of the SN they were probably caused by bipolar outflow *after* the launch of the explosion (possibly associated with late accretion by the NS; Janka et al. 2004a). This is supported by the fact that the NS appears displaced from the geometrical center of the reverse shock and of the ejecta knots almost perpendicular to the line of "jet" and "counter-jet"

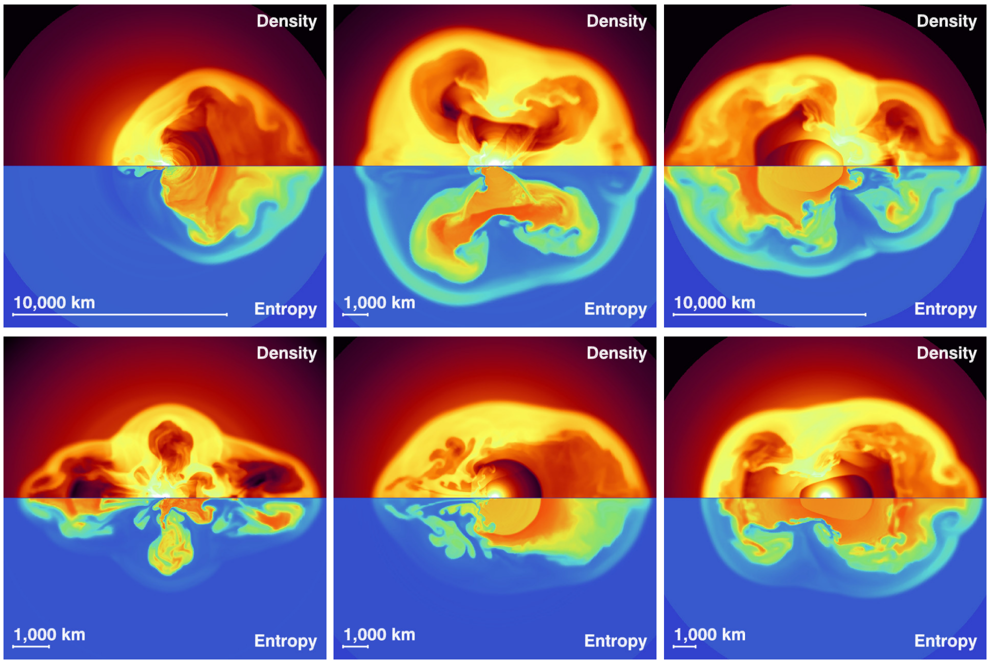

Figure 1. Snapshots of six out of currently 66 2D supernova simulations at 1 s after bounce, showing different morphology as the result of the highly nonlinear growth of anisotropies from random seed perturbations. The explosion energies at this time (still increasing in some cases) are 0.39, 0.96, 1.17, 0.33, 0.91, and 1.38×10^{51}erg, respectively (from top left to bottom right).

(Thorstensen, Fesen, & van den Bergh 2001, Gotthelf et al. 2001) so that a connection between NS recoil and the jet acceleration seems to be disfavored.

Since massive stars suffer from mass loss prior to collapse, they also lose significant amounts of angular momentum. Stellar evolution models including rotation (Heger, Langer, & Woosley 2000, Hirschi, Meynet, & Maeder 2004) show that convection and rotation-induced shear and circulation flows lead to efficient transport of angular momentum out of the stellar core. This is even enhanced when magnetic fields are taken into account. Nonmagnetic stars develop iron cores with rotation rates around 3–5 rad s^{-1} at the onset of collapse (Woosley, Heger, & Weaver 2002), whereas the remaining angular momentum is roughly 20 times smaller for magnetized cores (Heger et al. 2003a). While in the latter case the estimated spin period of the newly formed NS is in fairly good agreement with observations, the angular momentum in the collapsed stellar core in the former case exceeds the value corresponding to the critical frequency of a compact NS. With angular momentum being conserved during contraction, the NS would also gain a huge amount of rotational energy. For a 10 km object with a period of 1 ms the rotational energy is several 10^{52}erg. This energy is neither measured in the SN explosion nor released in the pulsar-powered remnant (calorimetry reveals the Crab Nebula, e.g., as the relic of a low-energetic SN), so would have to disappear via an invisible channel[1]. Alternatively, the rapidly rotating stellar core could be decelerated right after collapse, *before* contraction to NS size has happened. But a process which transports angular momentum sufficiently efficiently during this phase without braking the core rotation more efficiently during the much longer pre-collapse evolution, has not been identified.

In summary, it is unlikely that the cores of SN progenitors and newly formed NSs rotate rapidly. The explosion mechanism and observational properties of ordinary SNe, e.g., their explosion energies, Ni nucleosynthesis, anisotropies, and pulsar kicks, therefore call for an explanation that does not rely on the presence of large angular momentum or on the rotational amplification of magnetic fields. This is different from very energetic massive star explosions ("hypernovae") and gamma-ray burst events, where high rotation rates, jets, and possibly the formation of a black hole instead of a NS may be responsible for their particular characteristics (Heger et al. 2003b).

2. Low-Mode Hydrodynamic Instabilities

Large-scale deformation of the explosion and even a global asphericity, however, do not require rapid rotation of the SN core but can be caused by various kinds of hydrodynamic instabilities. Indeed we suspect that low-mode flow asymmetries may play a key role for explaining the observed inhomogeneities of the heavy-element distribution in SNe and SN remnants, the large polarization measurements of SNe, and the high space velocities of many young pulsars.

Herant (1995) speculated about the possibility of a stable $l = 1$, $m = 0$ (one inflow, one outflow) convective mode and discussed the potential importance of such a convective pattern for NS kicks up to nearly 1000 km/s. Herant's suggestion was motivated by Chandrasekhar's (1981) finding that the easiest modes to excite in thermally unstable fluid spheres are those belonging to $l = 1$. The situation discussed by Chandrasekhar resembles the one developing in the SN core by the convective instability of the neutrino-heated region between gain radius and SN shock, provided the radius of the latter is sufficiently much larger than the neutrinospheric radius and convection can therefore become "volume-filling". Thompson (2000) also predicted instability of the accretion shock to a global Rayleigh-Taylor mode that could lead to asymmetric shock expansion and a net impulse of several 100 km/s to the NS. Employing linear stability analysis, Foglizzo (2001, 2002) identified highest growth rates for non-radial $l = 1$ instability of shocked accretion flows due to the so-called "entropic-acoustic cycle" (Foglizzo & Tagger 2000) in which the infall of entropy and vorticity perturbations produces acoustic waves that propagate outward and create new entropy and vorticity perturbations when reaching the shock, thus closing an amplifying feedback cycle. Blondin, Mezzacappa, & DeMarino (2003) investigated the role of aspherical perturbations on the stability of standing accretion shocks by idealized hydrodynamic models, and found that oblique shocks feed vorticity and entropy in the postshock region and lead to growing turbulence and shock instability with an eventually dominant $l = 1$ or $l = 2$ mode.

[1] Gravitational-wave emission by r-modes has been discussed as such a possibility, but the saturation amplitude turned out to be too low (Arras et al. 2003, Woosley & Heger 2003).

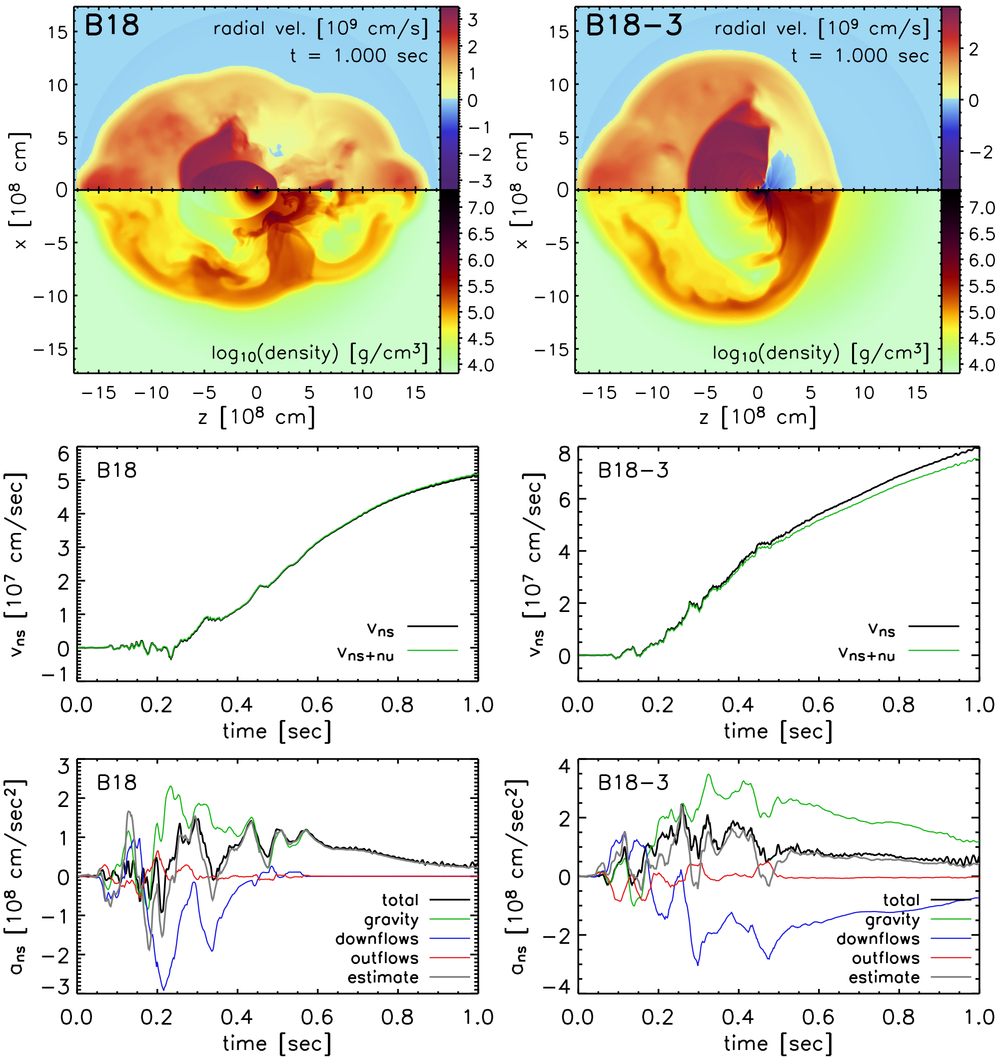

Figure 2. Two cases with large explosion asymmetry and dominant $l = 1$ mode of the neutrino-heated ejecta, both yielding high NS recoil velocities. The left model has a NS velocity of 520 km/s, the right model ~800 km/s after 1 s post-bounce evolution. In both cases the explosion energy is around 1.2×10^{51} erg, and the NS has still a very high acceleration at the end of our simulations. The upper plots display the morphology of the ejecta distribution at this time, the middle panels show the NS velocity as a function of time, and the lower panels the corresponding acceleration which is calculated from the negative of the rate of momentum change of the SN ejecta (curve 'total'). This net acceleration agrees with the summed contributions ('estimate') from the gravitational attraction between NS and surrounding gas ('gravity'), momentum transfer to the NS by downflows ('downflows'), and recoil by expanding, neutrino-heated gas ('outflows'). In the right model accretion continues until the simulation was stopped, and gravity and accretion both contribute to the net acceleration in the positive z-direction of the coordinate grid. In contrast, only gravitational forces provide the long-time acceleration of the left model. Anisotropic emission of neutrinos from the accretion layer as computed in our models makes only a minor effect for the NS acceleration (i.e., the difference between the two lines in the middle panels).

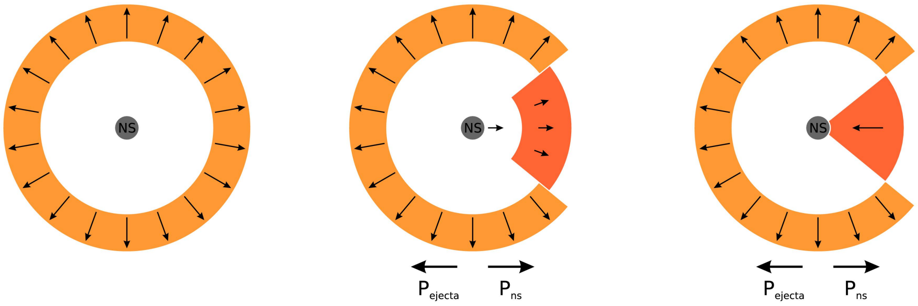

Figure 3. Graphical illustration how the NS is accelerated by a global asymmetry of the SN explosion. In case of a spherically symmetric distribution of the ejecta the NS remains at rest in the c.o.m. frame (left). A recoil is obtained mainly by the action of gravitational forces between NS and anisotropic ejecta (middle; corresponding to the case in the left panels of Fig. 2) or by the transfer of momentum (hydrodynamic forces) in long-lasting accretion flows to the compact remnant (right; cf. the model shown in the right panels of Fig. 2). The NS and ejected mass carry opposite momenta.

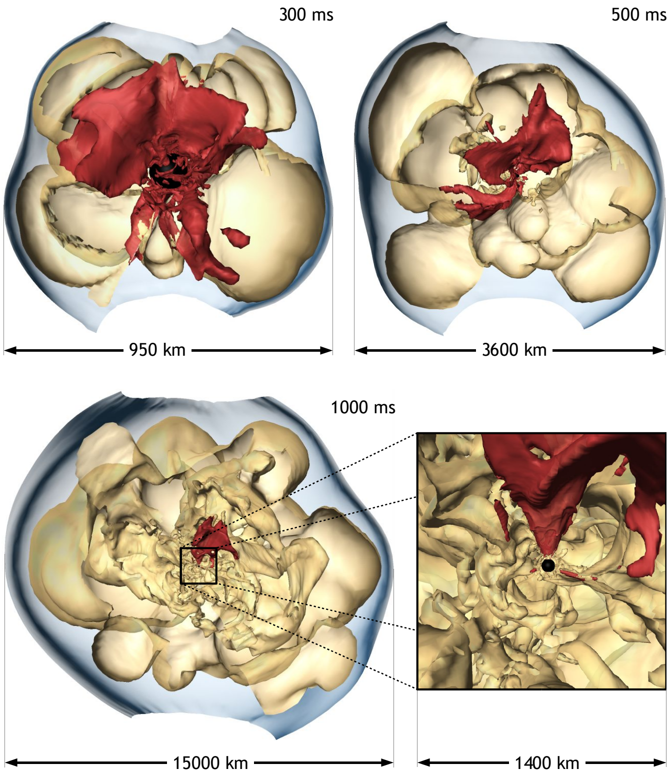

Figure 4. Snapshots from a 3D simulation at 300 ms (top left), 500 ms (top right) and 1000 ms (bottom) after bounce, showing the evolution of the neutrino-heated bubbles (visualized by surfaces of constant neutron-to-proton ratio), shock (enveloping surface), and accretion flows to the NS at the center (red iso-surfaces of the mass flow rate). Accretion is still going on at 1 s and has developed an $l = 1$ mode (lower right enlargement).

In fact, we have recently demonstrated the existence of such low-mode shock instabilities in the realistic SN environment by 2D hydrodynamic simulations with a detailed treatment of the equation of state and neutrino (ν) physics. The result did not depend on whether a simplified ν transport with ν luminosities imposed at an inner, contracting grid boundary (supposed to mimic the ν emission from the shrinking high-density core of the nascent NS) were used (Scheck et al. 2004), or whether full-scale SN models were calculated employing spectral (but still radial) transport by a variable Eddington factor technique for solving the moment equations of lepton number, energy, and momentum (Janka et al. 2004b,c). In both kinds of simulations we could find a dynamical behavior much alike the one reported by Blondin et al. (2003). When the explosion timescale is sufficiently long and the shock radius relative to the NS radius is sufficiently large, the convective cells in the ν-heating layer have time and volume to merge to huge structures (Fig. 1). We observed large non-radial shock oscillations and the development of a bipolar deformation with axis ratios up to more than 1:2. Finally the flow pattern behind the expanding, aspherical SN shock is dominated by $l = 1$ and $l = 2$ modes in self-similar expansion. The role of the vortical-acoustic instability in this process of mode merging is not obvious when violent convective activity is present. But we directly observed this kind of non-radial shock instability in cases where the onset of postshock convection was suppressed by our choice of a low ν luminosity from the inner boundary. With thus reduced ν heating behind the shock the negative entropy gradient was rather flat and high infall velocities of the gas behind the accretion shock (standing at a relatively small radius for these conditions) made the growth timescale of convection longer than the advection timescale. Thus Rayleigh-Taylor instabilities could not sprout. Nevertheless, the shock became unstable in a characteristic way by amplifying sound wave and vortex activity as envisioned by Foglizzo (2001, 2002).

3. Pulsar Kicks

In a large set of now 66 2D simulations for different $15\,M_\odot$ progenitors, with and without rotation, Scheck et al. (2004) found that the explosion energy increases with higher core ν luminosity, but the kick velocity imparted to the newly formed NS varies stochastically with the imposed initial nonradial perturbations (random seed with 0.1% amplitude on velocity) in the SN core (Figs. 1, 5). The anisotropy parameter $\alpha \equiv |\int \mathrm{d}m\, v_z| / \int \mathrm{d}m\, |v_{\mathrm{gas}}|$ decreases with higher explosion energy, E_{exp}, and thus with faster onset of the explosion (i.e., less time for low-mode growth). But since the net ejecta momentum $p_{\mathrm{ej}} \equiv \int \mathrm{d}m\, |v_{\mathrm{gas}}| \equiv M_{\mathrm{ej}}\, \langle|\vec{v}_{\mathrm{ej}}|\rangle$ increases essentially linearly with E_{exp}, the kick velocity $v_{\mathrm{ns}} = \alpha\, p_{\mathrm{ej}}/M_{\mathrm{ns}}$ shows no obvious correlation with E_{exp} (Fig. 5, upper left panel).

After 1 s of post-bounce evolution, we obtained NS velocities up to $800\,\mathrm{km\,s^{-1}}$ (to our knowledge this is the world record of *simulated* kicks), in many cases associated with still large acceleration so that final velocities well above $1000\,\mathrm{km\,s^{-1}}$ can be expected (Fig. 5, upper two panels). Figure 2 shows the record holder (right) and another high-velocity case, both having positive acceleration at the end of our simulations due to a combination of momentum transfer in case of ongoing accretion and the gravitational attraction of anisotropically distributed ejecta (Fig. 3). Anisotropic ν emission by accretion, which is included in our simulations, turned out to contribute to the NS acceleration only on a minor level (Fig. 2). The NS is kept fixed at the grid center because its motion is inhibited by the use of the inner boundary. In order to test this constraint we

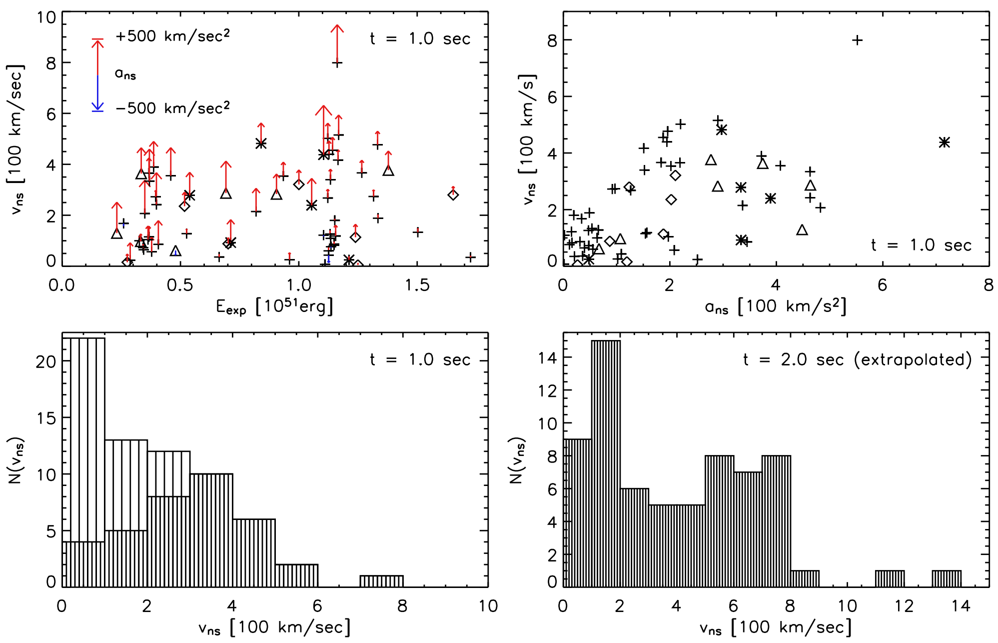

Figure 5. Statistics of currently 66 two-dimensional SN simulations which were carried out to 1 s after core bounce. The upper left plot shows the NS velocity, $v_{\rm ns}$, (acceleration indicated by arrows) vs. explosion energy $E_{\rm exp}$ and the upper right plot $v_{\rm ns}$ vs. the NS acceleration, $a_{\rm ns}$, at 1 s. Different symbols correspond to different $15\,M_\odot$ progenitors (see Scheck et al. 2004). The lower left panel displays the number of cases vs. NS velocity at the end of the simulations, binned in intervals of 100 km/s, with the dark-hatched area indicating those cases where $a_{\rm ns}$ is still larger than 150 km/s^2 after 1 s. Low-velocity neutron stars with small acceleration on the one hand and high-velocity stars with large acceleration on the other (see also the upper left plot) can lead to a bimodality which becomes visible when acceleration with the values at 1 s is assumed to continue for another second (lower right).

changed the frame of reference in some models by applying a coordinate transformation, adding a global, coherent acceleration on the whole grid with the value of the NS acceleration and opposite to its direction. Of course, the result for a particular choice of parameters changed, but no fundamental differences of the ensemble behavior were discovered. A first 3D simulation revealed also the development of an $l = 1$ mode in the accretion flow to the nascent NS within the first second of SN evolution (Fig. 4).

Although statements on the basis of our current sample of models (limited to $15\,M_\odot$ progenitors; 2D models instead of 3D; use of imposed core ν flux and simplified transport instead of fully self-consistent explosions; binary effects ignored) have to be made with caution, we propose here a speculative possibility for the origin of the bimodality of the observed velocity distribution (e.g., Arzoumanian, Chernoff, & Cordes 2002). In Fig. 5 one can see an indication of two populations in our sample: One big group (in the lower left corner of the upper right panel) has *low velocities and low acceleration* at 1 s; these models have not produced a dominant $l = 1$ mode in the ejecta. The second big group (towards the upper right in the same panel) has *high velocities and high acceleration* at 1 s due to the dominance of the $l = 1$ asymmetry. This situation is also visible in the lower left panel. The lower right panel of Fig. 5 shows the distribution extrapolated to a time 2 s after core bounce, assuming that the acceleration continues with a constant value between 1 s and 2 s. A bimodality becomes visible which appears very similar to the bold solid line in Fig. 3 of the Arzoumanian et al. (2002) paper. The minimum of the distribution between the low velocity ($v_{\rm ns} \lesssim 200\,{\rm km\,s^{-1}}$) and high velocity ($v_{\rm ns} \gtrsim 300\,{\rm km\,s^{-1}}$) components develops only on a timescale of possibly many seconds, because the large acceleration by an $l = 1$ asymmetry continues much beyond the first second after bounce.

4. Conclusions

We have presented results which demonstrate that hydrodynamic instabilities of the stalled accretion shock and the ν-heated postshock layer can lead to global anisotropy of the ejecta momentum and energy by the dominance of $l = 1, 2$ modes. These asymmetries do neither require rapid rotation nor the presence of strong magnetic fields in the SN core. They generically occur during the post-bounce accretion phase of the stalled SN shock provided the conditions during this phase are suitable. The ν-heating mechanism in combination with such low-mode hydrodynamic instabilities thus seems to yield a unique and consistent explanation for the SN explosion on the one hand, and for the observed asymmetries of SNe and the measured space velocities of pulsars including the bimodality of the NS velocity distribution on the other.

If our suggestion is valid (and, admittedly, the possible objections are still many), pulsar kicks would be a consequence of explosion asymmetries. In this case the SN ejecta and the NS would carry equal linear momenta in opposite directions, a fact that might allow for a verification by future observations. This would alleviate the need to invoke anisotropic ν emission from the nascent NS as an explanation for the pulsar kicks. Although already $\sim$1% asymmetry is sufficient to account for $300\,{\rm km\,s^{-1}}$, it is extremely difficult to produce emission anisotropies even at this low level, a fact which instigated claims for the presence of very strong magnetic fields and/or non-standard ν physics (for a review, see Lai, Chernoff, & Cordes 2001). Magnetars are often quoted in support of very high field strengths in NSs. However, there is no observational hint for a correlation of large fields and large pulsar velocities. Pulsar recoil by ν oscillations (Kusenko & Segre 1996), for example, requires the presence of fields with a very strong dipole component but also the existence of a sterile ν (Fuller et al. 2003 and references therein), because resonant flavor conversions of active ν's occur at densities below $10^4\,{\rm g\,cm^{-3}}$ far outside of the NS for the ν mass differences of solar and atmospheric oscillations. The fields for kicks of $300\,{\rm km\,s^{-1}}$ are estimated to be huge, typically $\gtrsim 10^{16}\,$G. The actual numbers are likely to be even higher (Janka & Raffelt 1998), because all estimates are based on adhoc assumptions about the asymmetry of the geometry without taking into account that any anisotropy of the ν emission unavoidably leads to an adjustment of the structure of the NS. The corresponding feedback typically reduces the emission asymmetry (Janka & Raffelt 1998). Meaningful estimates of the latter therefore require self-consistent models of structure and transport.

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