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Neutrino-driven wind and wind termination shock in supernova cores

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The neutrino-driven wind from a nascent neutron star at the center of a supernova expands into the earlier ejecta of the explosion. Upon collision with this slower matter the wind material is decelerated in a wind termination shock. By means of hydrodynamic simulations in spherical symmetry we demonstrate that this can lead to a large increase of the wind entropy, density, and temperature, and to a strong deceleration of the wind expansion. The consequences of this phenomenon for the possible r-process nucleosynthesis in the late wind still need to be explored in detail. Two-dimensional models show that the wind-ejecta collision is highly anisotropic and could lead to a directional dependence of the nucleosynthesis even if the neutrino-driven wind itself is spherically symmetric.

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1. Introduction

The site or sites where the r-process nucleosynthesis takes place are still unclear. To be a major source of r-process elements, an environment must fulfill two requirements: Firstly, it has to reproduce the r-process abundances pattern, and secondly, it should yield the total amount of r-process material in the present Galaxy. Due to this second constraint, several scenarios (e.g. neutron star mergers, GRB, disks) are not very likely to be the main site, although r-process elements are possibly produced there [1, 2, 3]. On the other hand, models for the core collapse supernova scenario, which was proposed already in 1957 by [4] and [5] as the r-process site, have so far not achieved to produce extreme conditions needed to generate the heaviest elements observed.

In principle, the supersonic neutrino-driven wind, which forms after the onset of the explosion, provides favorable conditions for the r-process – a high neutron abundance, short dynamical time scales, and high entropies. Several groups have studied this site by means of hydrodynamic supernova explosion simulation [6, 7], or by solving the stationary wind equations [8, 9].

In the past years, parametric models based on the solution of the general-relativistic steady-state wind equations have been developed [8, 9]. The relativistic treatment resulted in somewhat higher entropies than those found in Newtonian calculations [8]. However, also with this effect the common problem of all these studies remains that for "realistic parameters" (e.g. typical neutron star masses and radii) they do not find entropies sufficiently high for the r-process. However, none of these studies treated possible effects due to the interaction of the wind with preceding post-shock ejecta consistently. This interaction leads to the formation of a wind termination shock (or reverse shock) [10, 11], which can change the neutrino wind properties considerably.

We have performed one- and two-dimensional hydrodynamic simulations that start a few milliseconds after bounce and follow the evolution for several seconds after the onset of the explosion. This allows us to study systematically the influence of this reverse shock, which turns out to increase the wind entropies significantly. Here we describe briefly the numerics we are using and some of our first results.

2. Numerical setup

Our computational approach is described in detail in [12]. The initial data at $\sim$ 10ms after bounce are provided by Boltzmann simulations. We replace the inner part of the neutron star ($\rho \gtrsim 10^{13}$ g/cm^3) by an inner boundary, which allows us to avoid strong time step limitations and provides a degree of freedom for systematic variations. The contraction of the inner boundary can be parametrized by a time scale and a final neutron star radius. This can be justified by the fact that the neutron star evolution depends on the still incompletely known dense matter equation of state. The core neutrino luminosity is put in "by hand" at the inner boundary (below the neutrinosphere). Its value is chosen such that the explosion energy reaches typical values known from observations. We use a simplified neutrino transport treatment (a grey, characteristics-based scheme), which reproduces the results of Boltzmann transport simulations qualitatively. However, quantities like the electron fraction should be taken with caution. Our hydrodynamics code is Newtonian, but we account for relativistic effects by using corrections in the gravitational potential [13]. This approximation has been shown to yield results very similar to the full general relativistic treatment.

3. Results

After the explosion has been launched successfully, the supernova shock propagates outwards and the density around the neutron star decreases. Ongoing neutrino-energy deposition leads to the formation of a neutrino-driven wind that emerges from the neutron star surface. The matter in the wind is accelerated to supersonic velocities, hits the slower moving preceding ejecta and is strongly decelerated in a wind termination shock (see Fig.1).

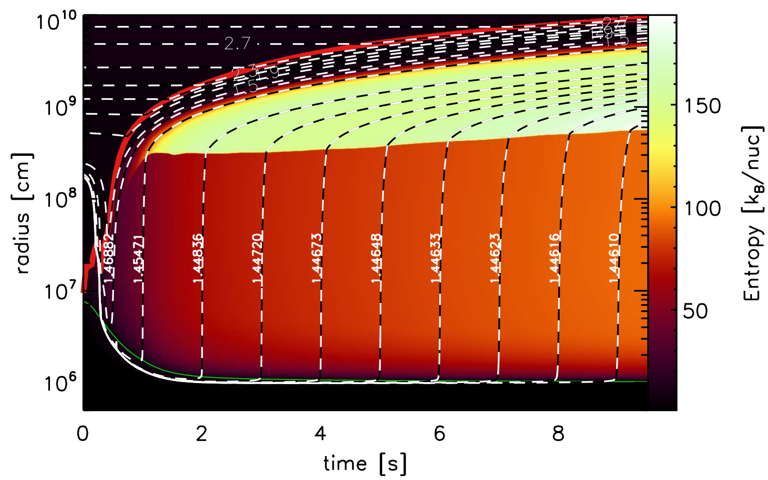

Figure 1: Mass shell and entropy (color) plot for a one-dimensional model (based on a $15M_{\odot}$ progenitor) that attains an explosion energy of ~ 1.2 bethe. The green line corresponds to the neutron star which shrinks to a radius of ~ 10 km. The red line is the shock radius. The dashed lines are mass shell trajectories (the baryonic mass below a mass shell is given in $M_{\odot}$). In the wind phase the mass shells move to larger radii in a very short time corresponding to high wind velocities. When the wind velocity becomes supersonic in the frame of the slower-moving material outside (i.e. in the region where the mass shell lines expand more slowly), a reverse shock forms. This leads to a jump in the entropy (at $\sim 5 \cdot 10^{8}$ cm).

Figure 2 shows characteristic quantities from a one-dimensional simulation as functions of radius for different times. In the *wind phase*, the velocity increases, becomes supersonic, and tends to an asymptotic value. Also the entropy reaches a constant maximum value where the neutrino energy deposition rate (q in Fig.2) becomes negligible. The quantities characteristic for the wind (velocity, entropy, ...) are qualitatively and, for the same values for the neutrino heating rate, even quantitatively in agreement with general relativistic stationary wind solutions (see e.g. [9]). The wind entropy increases with time due to the decrease of the neutrino luminosity (see [14] for an analytic discussion of how the entropy depends on the neutrino properties). The highest wind entropy obtained in our simulations is not as high as those found in previous wind studies. The reason is that the neutrino luminosities even at the end of our simulations are higher than the lowest values considered for stationary wind solutions. This explains also the larger mass flux in the wind ($\dot{M} \approx 10^{-4} M_{\odot}/\mathrm{s}$) in our case. Another nucleosynthesis-relevant quantity, the electron fraction Y_{e}, evolves from proton richness ($Y_{\mathrm{e}} > 0.5$) just after the onset of the explosion (as found also in Boltzmann simulations with artificial explosions [15, 16]) to neutron richness ($Y_{\mathrm{e}} < 0.5$) at $t > 3$s after bounce. In the simulation presented here we have short expansion time scales which should prevent a large fraction of alpha particles from recombination to seed nuclei. Consequently the situation favors many free neutrons to remain unbound and thus a high neutron-to-seed ratio after the α-rich freeze-out phase.

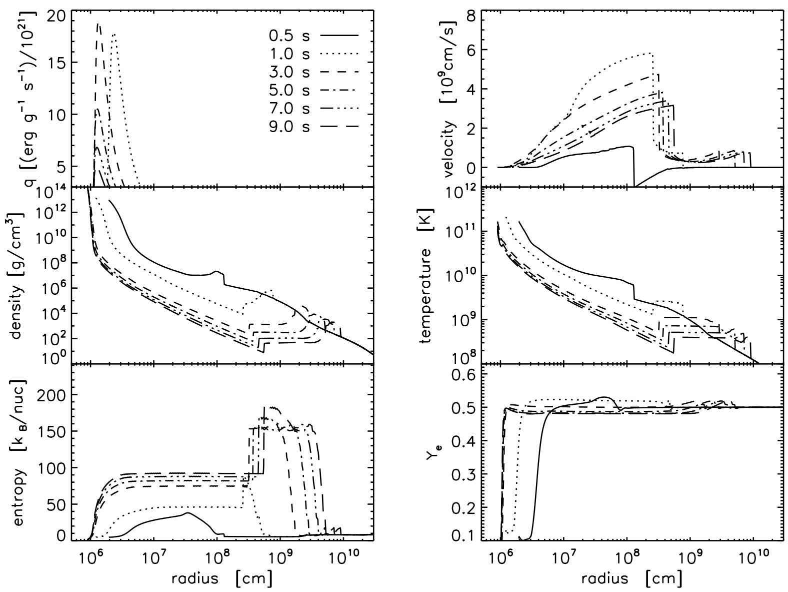

Figure 2: Radial profiles at different times after bounce for the neutrino energy deposition rate (q), density, entropy (left column), velocity, temperature and Y_e (right column). The effect of the reverse shock is clearly visible as a jump of the wind entropy by a factor of two.

In Figure 2 one can also see how the supersonic outflow hits the slower preceding supernova ejecta, and is decelerated in the wind termination shock, which leads to a sudden increase of density, temperature, and entropy. From the Rankine-Hugoniot conditions it is straight forward to demonstrate that the jump in the entropy increases with the square of the wind velocity. Temperature and density decay with time much more slowly after the wind matter was decelerated by the reverse shock. The conditions established during that phase ($T_9 \sim 0.5-1$, $\rho \sim 100-10^4\,\mathrm{g/cm^3}$) suggest possibly important consequences for the nucleosynthesis in the supernova ejecta. Detailed nucleosynthesis calculations, however, are needed to explore the exact effects.

We have performed simulations of the kind described here, with varied conditions at the inner boundary (different neutron star contractions and neutrino luminosities) for different explosion energies and several progenitor stars. In all cases the wind termination shock developed and had qualitatively similar consequences. Interesting quantitative differences will be analyzed in a paper in preparation.

The reverse shock forms also in our *two-dimensional simulations* (see Fig. 3 for an example). Interestingly, the conditions are strongly dependent on the direction and suggest a very anisotropic distribution of the nucleosynthetic products of the neutrino-driven winds. This also raises the question how robust the condition can be in this environment for r-process nucleosynthesis.

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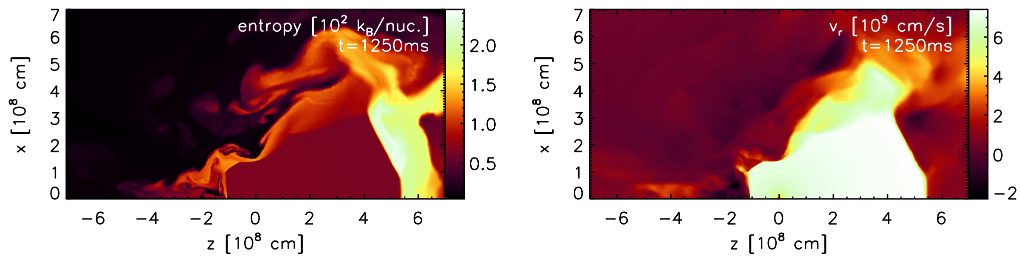

Figure 3: Two dimensional simulations. Entropy and velocity at 1.2 seconds after core bounce. Note the highly aspherical distribution of the ejecta. The effect of the reverse shock on the entropy leads to similar maximum entropies as in one dimension.

4. Conclusions

Our work demonstrates that over a wide variation of conditions (neutron star parameters, progenitors, spherical symmetry or multi-dimensional environment) the wind termination shock may have non-negligible influence on the nucleosynthesis conditions in the neutrino-driven winds. It does not only increase the wind entropy by up to a factor of two, but also changes the time evolution of density and temperature in an interesting way. Nucleosynthesis calculations are needed to study the exact consequences of this so far incompletely explored feature of supernova ejecta dynamics.

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References

[1] Y.-Z. Qian. Supernovae versus Neutron Star Mergers as the Major R-Process Sources. *ApJ*, 534:L67–L70, May 2000.

[2] C. Freiburghaus, S. Rosswog, and F.-K. Thielemann. R-Process in Neutron Star Mergers. *ApJ*, 525:L121–L124, November 1999.

[3] A. G. W. Cameron. Some Properties of r-Process Accretion Disks and Jets. *ApJ*, 562:456–469, November 2001.

[4] E. M. Burbidge, G. R. Burbidge, W. A. Fowler, and F. Hoyle. Synthesis of the Elements in Stars. *Reviews of Modern Physics*, 29:547–650, 1957.

[5] A. G. W. Cameron. Nuclear Reactions in Stars and Nucleogenesis. *PASP*, 69:201–+, June 1957.

[6] S. E. Woosley, J. R. Wilson, G. J. Mathews, R. D. Hoffman, and B. S. Meyer. The r-process and neutrino-heated supernova ejecta. *ApJ*, 433:229–246, September 1994.

[7] K. Takahashi, J. Witti, and H.-T. Janka. Nucleosynthesis in neutrino-driven winds from protoneutron stars II. The r-process. *A&A*, 286:857–869, June 1994.

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[8] K. Otsuki, H. Tagoshi, T. Kajino, and S.-y. Wanajo. General Relativistic Effects on Neutrino-driven Winds from Young, Hot Neutron Stars and r-Process Nucleosynthesis. *ApJ*, 533:424–439, April 2000.

[9] T. A. Thompson, A. Burrows, and B. S. Meyer. The Physics of Proto-Neutron Star Winds: Implications for r-Process Nucleosynthesis. *ApJ*, 562:887–908, December 2001.

[10] H.-T. Janka and E. Mueller. Neutrino heating, convection, and the mechanism of Type-II supernova explosions. *A&A*, 306:167–+, February 1996.

[11] R. Tomàs, M. Kachelrieß, G. Raffelt, A. Dighe, H.-T. Janka, and L. Scheck. Neutrino signatures of supernova forward and reverse shock propagation. *Journal of Cosmology and Astro-Particle Physics*, 9:15–+, September 2004.

[12] L. Scheck, K. Kifonidis, H.-T. Janka, and E. Müller. Multidimensional supernova simulations with approximative neutrino transport. I. Neutron star kicks and the anisotropy of neutrino-driven explosions in two spatial dimensions. *A&A*, 457:963–986, October 2006.

[13] A. Marek, H. Dimmelmeier, H.-T. Janka, E. Müller, and R. Buras. Exploring the relativistic regime with Newtonian hydrodynamics: an improved effective gravitational potential for supernova simulations. *A&A*, 445:273–289, January 2006.

[14] Y.-Z. Qian and S. E. Woosley. Nucleosynthesis in Neutrino-driven Winds. I. The Physical Conditions. *ApJ*, 471:331–+, November 1996.

[15] R. Buras, M. Rampp, H.-T. Janka, and K. Kifonidis. Two-dimensional hydrodynamic core-collapse supernova simulations with spectral neutrino transport. I. Numerical method and results for a 15 $M_\odot$ star. *A&A*, 447:1049–1092, March 2006.

[16] C. Fröhlich, G. Martínez-Pinedo, M. Liebendörfer, F.-K. Thielemann, E. Bravo, W. R. Hix, K. Langanke, and N. T. Zinner. Neutrino-Induced Nucleosynthesis of A$>$64 Nuclei: The νp Process. *Physical Review Letters*, 96(14):142502–+, April 2006.