The Physics of Protoneutron Star Winds

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Abstract: The work presented here is from that of Thompson, Burrows, & Meyer 2001, ApJ, 562, 887.

We present results from a study of spherical transonic neutrino-driven winds from protoneutron stars. We solve the equations of steady-state general-relativistic hydrodynamical flow with a general neutrino energy deposition function in a Schwarzschild metric, including the effects of gravitational redshift and the bending of null geodesics on the neutrino-matter interactions. We find that only outflows from extremely massive ($\gtrsim 2.0\,\mathrm{M}_\odot$), compact ($R \lesssim 10\,\mathrm{km}$), and highly neutrino-luminous protoneutron stars attain neutron-to-seed ratio sufficient for production of 3^{rd}-peak r-process nuclides.

Results: Four parameters determine the viability of any astrophysical site as a candidate for generation of the r-process elements: the electron fraction (Y_e), the entropy (s), the dynamical timescale (τ_{dyn}) at a characteristic temperature (T, typically 0.5 MeV) for nucleosynthesis, and a characteristic mass outflow rate ($\dot{M}$), which sets the total mass ejected in r-process elements. See slides 2, 5, & 7. Generally, lower Y_e, higher s, and shorter τ_{dyn} yield higher neutron-to-seed ratio. In winds with higher neutron-to-seed ratio, r-process nucleosynthesis proceeds higher in atomic number. Protoneutron star (PNS) winds, because of both their intrinsic neutron-richness and association with supernovae (SNe), are thought to be a likely astrophysical site for the r-process.

For an mpeg movie that shows core-collapse and subsequent explosion of a massive star, followed by PNS wind emergence, see http://astron.berkeley.edu/~thomp/yemv.mpeg (Slide 6). This movie is from a simulation by Burrows, Hayes, & Fryxell 1995, ApJ, 450, 830. Note that the wind is *distinct* from the actual SN explosion, but follows it almost immediately. The wind attends the Kelvin-Helmholtz cooling phase ($\sim 10-20$ seconds) of the PNS during which a multiple of 10^{53} erg in binding energy will be lost by the PNS as neutrino radiation. A small amount of this energy will be deposited in the hot surface layers of the PNS, ablating material from the atmosphere, and driving an outflow to infinity.

In the study described here, we derive Y_e, s, τ_{dyn}, and $\dot{M}$ for a large number of neutrino-driven PNS wind models. The formalism is presented in slides 9 & 10. The basic wind results and profiles are shown in slides $11-15$. We find important correlations between the various quantities and map the parameter space available to PNS winds in slides 16 & 17 - comparing the region inhabited by the wind solutions with the region in which the heavy r-process nuclides can be produced.

In slide 17, we show PNS wind models in the plane of τ_{dyn} versus s. The blue lines are constructed of points, each of which is a separate steady-state wind model with different neutrino spectral characteristics or PNS radius. The four blue lines are for 1.4, 1.6, 1.8, and $2.0\,\mathrm{M}_\odot$ PNSs, respectively. On each line, the point of lowest entropy is the point of maximum luminosity and largest radius. As we decrease the radius of the PNS, for a given PNS mass, the model produces higher entropy. At 10 km we halt the radial contraction of each model and only decrease the neutrino luminosity. Each model evolves almost horizontally in the $\tau_{\mathrm{dyn}} - s$ plane to much longer τ_{dyn} and moderately larger s. The thick red line shows the point on each model at which the mass outflow rate becomes too low to explain the total r-process budget of the galaxy, assuming that all such SNe produce r-process nuclei (see slides 3,4, & 5). Above and to the left of the magenta line is the region in the $\tau_{\mathrm{dyn}} - s$ plane where production of the 3^{rd}-peak r-process nuclei is likely (taken from Meyer & Brown 1997, ApJS, 112, 197).

We find that only PNSs with very large gravitational masses ($\gtrsim 2.0\,\mathrm{M}_\odot$), and small coordinate radii ($R \lesssim 10\,\mathrm{km}$) produce robust r-process nucleosynthesis, up to and including the 3^{rd}-peak. PNSs with $M = 1.4\,\mathrm{M}_\odot$ and $R = 10\,\mathrm{km}$ do not produce r-process nuclei beyond $A \sim 100$ (Slide 18).