# The $r$-process in prompt explosions from collapsing O-Ne-Mg cores

S. Wanajo[a], N. Itoh[a], K. Nomoto[b], Y. Ishimaru[c], and T. C. Beers[d]

[a]Department of Physics, Sophia University, 7-1 Kioi-cho, Chiyoda-ku, Tokyo, 102-8554

[b]Department of Astronomy, School of Science, University of Tokyo, Bunkyo-ku, Tokyo, 113-0033

[c]Department of Physics and Graduate School of Humanities and Sciences, Ochanomizu University, 2-1-1 Otsuka, Bunkyo-ku, Tokyo 112-8610

[d]Department of Physics/Astronomy, Michigan State University, E. Lansing, MI 48824

We examine $r$-process nucleosynthesis in a "prompt supernova explosion" from an $8 - 10 M_\odot$ progenitor star. We simulate energetic prompt explosions by enhancement of the shock-heating energy, in order to investigate conditions necessary for the production of $r$-process nuclei in such events. The $r$-process nucleosynthesis is calculated using a nuclear reaction network code including relevant neutron-rich isotopes with reactions among them. The highly neutronized ejecta ($Y_e \approx 0.14 - 0.20$) leads to robust production of $r$-process nuclei; their relative abundances are in excellent agreement with the solar $r$-process pattern.

## 1. Introduction

The astrophysical origin of the rapid neutron-capture ($r$-process) species has been a long-standing mystery. So far, the "neutrino wind" scenario has been believed to be the most promising astrophysical site of the $r$-process. Even this scenario, however, encounters some difficulties [16,11]. Recent chemical evolution studies imply the dominant source of $r$-process elements to be the low-mass end of the supernova mass range, such as stars of $8 - 10 M_\odot$ [5,6]. The question of whether $8 - 10 M_\odot$ stars that form O-Ne-Mg cores can explode is still open [15]. Hillebrandt et al. [4] have obtained a prompt explosion of a $9 M_\odot$ star with a $1.38 M_\odot$ O-Ne-Mg core [8], while others, using the same progenitor, have not [2,1]. Mayle & Wilson [7] obtained an explosion, not by a prompt shock, but by late-time neutrino heating. The purpose of this study is to investigate conditions necessary for the production of $r$-process nuclei obtained in purely hydrodynamical models of prompt explosions of collapsing O-Ne-Mg cores, and to explore some of the consequences if those conditions are met (see [13,14] for more detail). The core collapse and the subsequent core bounce are simulated by a one-dimensional hydrodynamic code with Newtonian gravity (§ 2). The $r$-process nucleosynthesis in these explosions is then calculated with the use of a nuclear reaction network code (§ 3). A summary follows in § 4.

## 2. Prompt Explosion

A pre-supernova model of a $9M_\odot$ star is taken from Nomoto [8], which forms a 1.38 $M_\odot$ O-Ne-Mg core. We link this core to a one-dimensional implicit Lagrangian hydrodynamic code with Newtonian gravity. The equation of state of nuclear matter (EOS) is taken from Shen et al. [9]. We find that a very weak explosion results, where no $r$-processing is expected. In order to examine the possible operation of the $r$-process in the explosion of this model, we artificially obtain explosions with typical energies of $\sim 10^{51}$ ergs by application of a multiplicative factor ($f_{\rm shock}$) to the shock-heating term in the energy equation (Figure 1). This is clearly not a self-consistent approach, and a further study is needed to conclude whether such a progenitor star explodes or not. Table 1 lists the multiplicative factor ($f_{\rm shock}$), explosion energy ($E_{\rm exp}$), ejected mass ($M_{\rm ej}$), and minimum $Y_e$ in the ejecta obtained for each model.

Table 1
Results of Core-Collapse Simulations

| Model | $f_{\rm shock}$ | $E_{\rm exp}$ ($10^{51}$ ergs) | $M_{\rm ej}$ ($M_\odot$) | $Y_{e,\rm min}$ |
|---|---|---|---|---|
| Q0... | 1.0 | 0.018 | 0.0079 | 0.45 |
| Q3... | 1.3 | 0.10 | 0.029 | 0.36 |
| Q5... | 1.5 | 1.2 | 0.19 | 0.30 |
| Q6... | 1.6 | 3.5 | 0.44 | 0.14 |

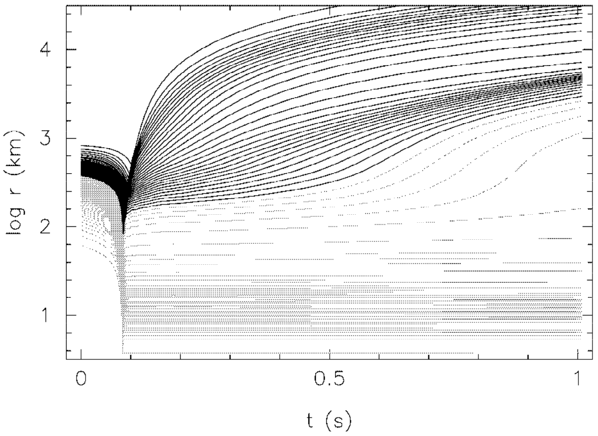

Figure 1. Time variation of the radii for selected mass points (with roughly an equal mass interval) for model Q6. The ejected mass points are denoted in black, while those of the remnant are in grey.

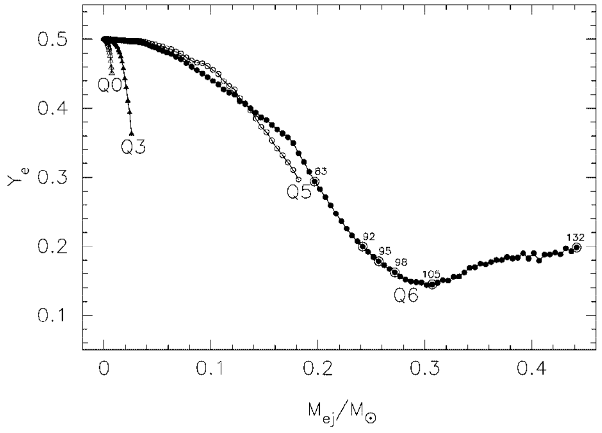

Figure 2. $Y_e$ distribution in the ejected material in models Q0 (open triangles), Q3 (filled triangles), Q5 (open circles), and Q6 (filled circles). The surface of the O-Ne-Mg core is at mass coordinate zero.

In Figure 2 the electron fraction in the ejecta of each model is shown as a function of the ejected mass point, $M_{\rm ej}$. The inner regions approach very low $Y_e$, 0.30 and 0.14 for models Q5 and Q6, respectively, owing to their rather high density ($\sim 10^{11}$ g cm$^{-3}$) at the time of core bounce. The trend of the $Y_e - M_{\rm ej}$ relation up to $M_{\rm ej} \sim 0.2 M_\odot$ is similar in these models. In the subsequent sections, therefore, we focus only on model Q6, which is taken to be representative of cases where $r$-process nucleosynthesis occurs. The ejected mass, $M_{\rm ej}$, is thus taken to be a free parameter, instead of simulating many other models by changing $f_{\rm shock}$.

## 3. The $r$-Process

The yields of $r$-process nucleosynthesis species are obtained by application of an extensive nuclear reaction network code that consists of $\sim$ 4000 species. The mass-integrated abundances from the surface (zone 1) to the zones 83, 92, 95, 98, 105, and 132 are compared with the solar $r$-process abundances in Figure 3. The latter is scaled to match the height of the first ($A = 80$) and third ($A = 195$) peaks of the abundances in models Q6a-b and Q6c-f, respectively. As can be seen in Figure 3, a solar $r$-process pattern for $A \gtrsim 130$ is naturally reproduced in models Q6c-f, while models Q6a-b fail to reproduce the third abundance peak. This implies that the region with $Y_e < 0.20$ must be ejected to account for production of the third $r$-process peak. Furthermore, to account for the solar level of thorium ($A = 232$) and uranium ($A = 235, 238$) production, the region with rather low $Y_e$ ($< 0.18$) must be ejected.

We find that, for models Q6c-f, the lighter $r$-process nuclei with $A < 130$ are somewhat deficient compared to the solar $r$-process pattern (Figure 3c-e). This trend can be also seen in the observational abundance patterns of the highly $r$-process-enhanced, extremely metal-poor stars CS 22892-052 [10] and CS 31082-001 [3]. This is in contrast to the previous results obtained for the neutrino wind scenario, which significantly *overproduce* the nuclei with $A \approx 90$ [16,11]. The nuclei with $A < 130$ can be supplied by slightly less energetic explosions, like models Q6a-b (Figures 3a-b). Figure 3 implies that the production of thorium and uranium differs from model to model, even though the abundance pattern seems to be *universal* between the second and third $r$-process peaks. Thus, the use of Th/Eu as a cosmochronometer should be regarded with caution, at least until the possible variations can be better quantified; U/Th might be a far more reliable chronometer [12,13].

## 4. Summary

We have examined the $r$-process nucleosynthesis obtained in the prompt explosion arising from the collapse of a $9 M_\odot$ star with an O-Ne-Mg core. The core collapse and subsequent core bounce were simulated with a one-dimensional, implicit, Lagrangian hydrodynamic code with Newtonian gravity. We obtained a very weak explosion with an explosion energy of $\sim 2 \times 10^{49}$ ergs. No $r$-processing occurred in this model, because of the high electron fraction ($\gtrsim 0.45$) with low entropy ($\sim 10 N_A k$). We further simulated energetic explosions by an artificial enhancement of the shock-heating energy. This resulted in an explosion energy of $\gtrsim 10^{51}$ ergs and an ejected mass of $\gtrsim 0.2 M_\odot$. Highly neutronized matter ($Y_e \approx 0.14$) was ejected, which led to strong $r$-processing. The result was in good agreement with the solar $r$-process pattern, in particular for nuclei with $A > 130$.

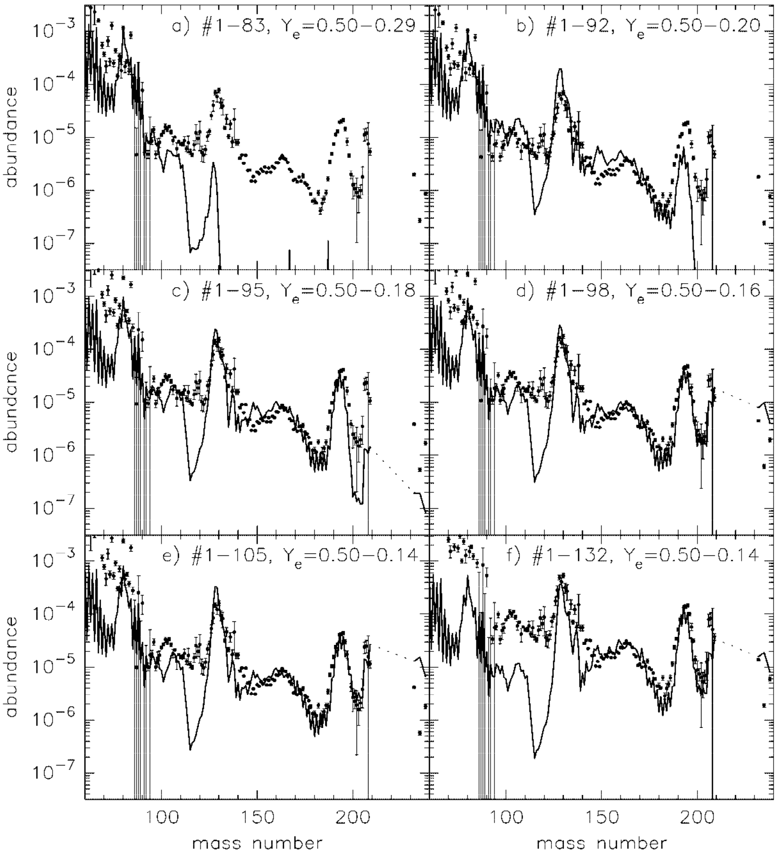

Figure 3. Mass-averaged $r$-process abundances (line) as a function of mass number, which are compared with the solar $r$-process abundances (points).

## REFERENCES

1. Baron, E., Cooperstein, J., & Kahana, S. 1987, ApJ, 320, 300
2. Burrows, A. & Lattimer, J. M. 1985, ApJ, 299, L19
3. Hill, et al. 2002, A&A, 387, 560
4. Hillebrandt, W., Nomoto, K., & Wolff, G. 1984, A&A, 133, 175
5. Ishimaru, Y. & Wanajo, S. 1999, ApJ, 511, L33
6. Ishimaru, Y., Wanajo, S., Aoki, W., & Ryan, S. G. 2004, ApJ, 600, L47
7. Mayle, R. & Wilson, J. R. 1988, ApJ, 334, 909
8. Nomoto, K. 1984, ApJ, 277, 791
9. Shen, H., Toki, H., Oyamatsu, K., & Sumiyoshi, K. 1998, Nucl. Phys. A, 637, 435
10. Sneden, C., et al. 2003, ApJ, 591, 936
11. Wanajo, S., Kajino, T., Mathews, G. J., & Otsuki, K. 2001, ApJ, 554, 578
12. Wanajo, S., Itoh, N., Ishimaru, Y., Nozawa, S., & Beers, T. C. 2002, ApJ, 577, 853
13. Wanajo, S., Tamamura, M., Itoh, N., Nomoto, K., Ishimaru, Y., Beers, T. C., & Nozawa, S. 2003, ApJ, 593, 968
14. Wanajo, S., Goriely, S., Samyn, M., & Itoh, N. 2004, ApJ, 606, 1057
15. Wheeler, J. C., Cowan, J. J., & Hillebrandt, W. 1998, ApJ, 493, L101
16. Woosley, S. E., Wilson, J. R., Mathews, G. J., Hoffman, R. D., & Meyer, B. S. 1994, ApJ, 433, 229