R-Process in Collapsing O/Ne/Mg Cores

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ABSTRACT

Several circumstantial arguments point to the formation of the third r-process peak at A$\sim$190, near platinum, in stars of mass of $\sim$ 8-10 M$_\odot$: 1) The delayed production of europium with respect to iron imposes a time scale that restricts the progenitor stars to M$\lesssim$10 M$_\odot$; 2) the r-process demands a dominant robust mechanism at least for Z$\geq$56, barium and above, since the relative abundance pattern of those r-process elements in the low-metallicity stars, [Fe/H] $<$ -2, is consistent with the solar pattern; 3) stars of $\sim$ 8-10 M$_\odot$ produce nearly identical degenerate O/Ne/Mg cores that collapse due to electron capture; and 4) the resulting low-mass cores may produce both an r-process in a prompt explosion and a subsequent r-process in a neutrino driven wind. A special case of the r-process singles out low entropies for initial Y$_e$ $\sim\bar{Z}$/A, where $\bar{Z}$ is the mean atomic number of the seed nuclei and A is the atomic weight of the target. For $\bar{Z}$ $\simeq$35 and Y$_e$ $\simeq$0.18 the A$\simeq$190 peak results in a natural way. The prompt explosion of an O/Ne/Mg core yields low entropy, S$\sim$15, and low electron fraction, Y$_e$ $\simeq$0.2, and hence may produce a reasonable r-process peak at A$\simeq$190, as well as all of the r-process elements with Z$\geq$ 56. The possible differences in the ν-driven wind and associated r-process due to the low-mass neutron stars expected in this mass range are also discussed.

Subject headings: Galaxy: evolution — nuclear reactions, nucleosynthesis, abundances — stars: abundances — Supernovae: general

1. Introduction

The r-process defined by the classic paper of Burbidge, Burbidge, Fowler, & Hoyle (1957) remains one of the most intriguing in the study of nucleosynthesis. The actual r-process site has still not been identified, although supernovae are strongly suspected. Cowan, Thielemann, & Truran (1991), Mathews, Bazan, & Cowan (1992) and Meyer (1994) discuss possible sites. Recent developments in both observations and theory have brought this process into special relief.

Of particular importance have been studies of the abundances of r-process and other elements in halo stars of low metallicity (Spite & Spite 1978, Gilroy et al. 1988, Sneden et al. 1996, Burris et al. 1997 and references therein). The r-process elements cannot be synthesized internally in low-mass stars. The presence of these elements in the oldest Galactic stars (i.e. early in the history of the Galaxy) points to rapidly evolving and hence massive progenitors for the r-process. Two important conclusions have recently come into focus.

One is the evidence that the production of iron at low metallicity, and hence early in the history of the Galaxy, occurred substantially before the production of the r-process element europium. At the lowest metallicities the stellar abundance of europium begins to deviate from a strict scaling with the abundance of iron (Gilroy et al. 1988). This suggests that the stars that produce iron must have evolved before the stars that produced the europium. The data were interpreted by Mathews, Bazan, & Cowan (1992) as an evolutionary time-delay for r-process production by $\sim 10^8$ yr that is related to the masses of the r-process progenitors. While noting there were uncertainties in their model calculations, Mathews et al. found that a model in which iron came from massive stars, $\gtrsim 15$ $M_\odot$, and europium came from stars of $\sim$ 8-10 $M_\odot$ gave a good fit to the stellar abundance data.

An equally striking conclusion arises from recent space-based observations (Cowan et al. 1996, Sneden et al. 1997) in conjunction with ground-based observations (Cowan et al. 1995, Sneden et al. 1996, Cowan et al. 1997a) yielding abundance data from just above the second *r*-process peak (A $\sim$ 130) to beyond the third *r*-process peak (A $\sim$ 190) at low metallicity, [Fe/H] ranging from -2 down to of order -3. The detailed distributions of the *r*-process elements at these low metallicities, at least for the elements with Z $\geq$ 56, is consistent with a scaled solar system distribution. This strongly implies that there has been a single dominant *r*-process working throughout the history of the Galaxy. Although there is some evidence for more than one *r*-process mechanism, the conclusion is that the dominant process must be rather robust, not an integration over broad ranges of initial seeds and other physical conditions.

On the theoretical side, explorations of *r*-process conditions also suggest only a limited number of environments could be responsible for producing an abundance pattern consistent with the solar one (Thielemann et al. 1997). The general physical conditions necessary to create the *r*-process have been continually refined (Takahashi et al. 1994; Fuller & Meyer 1995; Hoffman et al. 1996). The interesting physics of ν-driven winds has been proposed and explored in greatly increasing detail (Woosley & Hoffman 1992; Howard et al. 1993; Takahashi, Witti, & Janka 1994; Qian & Woosley 1996; Hoffman, Woosley & Qian 1997). The ν-driven wind, while based on very enticing physics, has not yet proven to give adequate results, especially for the third *r*-process peak (Takahashi et al. 1994). It is not clear whether this is an intrinsic problem with the physics of the process or whether it has been applied in an inappropriate context. In particular, most of the focus of the work on the *r*-process has been on collapsing iron cores of massive stars. This is because these models are directly relevant to SN 1987A and most of the collapse models currently being studied are representative of this progenitor mass, $\sim$ 15 – 20 $M_{\odot}$. Given the evidence from the europium and the arguments we present here, this may prove to be the wrong mass range for the *r*-process.

Aside from the evidence from europium that stars of mass less than ~ 10 $M_\odot$ are the relevant place to look for the *r*-process, these stars are of great intrinsic interest. It is *a priori* clear that, if they explode, stars in the mass range $\sim$ 8-10 $M_\odot$ will be a substantial fraction of all supernovae and that they will undergo core collapse that is significantly different than that of the iron cores of more massive stars. This is because just above $\sim$8 $M_\odot$, the limit to produce degenerate C/O cores, stars produce degenerate O/Ne/Mg cores (Nomoto 1984). The upper limit to this process is somewhat uncertain, but it may be about 12 $M_\odot$, above which stars produce iron cores (Nomoto 1987).

There are two significant properties of the final evolution of stars in the mass range $\sim$ 8-10 $M_\odot$. First, the evolution of the cores should be virtually identical. This alone makes them an enticing site for a robust *r*-process, independent of the evidence from europium. At higher masses stars undergo non-monotonic core evolution (Marom & Barkat 1990; Woosley & Weaver 1995), with various core masses and various envelope masses and structures. This is not conducive to production of a single robust *r*-process, even if a compelling argument for the ν-driven wind could be made for the massive stars. The second attribute of these low-mass stars is that they collapse by electron capture. This gives their cores an intrinsically different (lower) initial Y_e. They also have a lower core mass, a proper mass of ~ 1.4 $M_\odot$ and so they will form neutron stars with significantly lower mass but larger radii. Finally, the cores burn oxygen during the collapse, a process that does not halt the collapse, but can slow the infall and alter the collapse adiabat (Hillebrandt, Nomoto, & Wolff 1984; but also see Burrows & Lattimer 1985). The locus of oxygen burning can define an even smaller collapsing iron core, ~ 1.2 $M_\odot$, in the calculation of Hillebrandt et al. The smaller mass is intrinsically better able to produce a robust explosion because the envelope is more loosely bound with no dense mantle and is separated from the core by a steep density gradient. Once a strong shock is launched, stalling in the mantle is not an issue. This is the reason why such collapsing cores remain the only potential candidates for prompt explosions. In any case, these stars must produce an interesting class of neutron stars if they proceed to collapse and they clearly have properties of relevance to the general issue of the r-process.

2. Collapse of O/Ne/Mg Cores

The collapse of O/Ne/Mg cores has received relatively little attention in the gravitational collapse community. One especially relevant work in this regard is the paper by Hillebrandt, Nomoto, & Wolff (1984) in which the electron-capture-induced collapse of such a core was followed in some detail. This degenerate core did not reach the Chandrasekhar mass because of the destabilizing effects of electron capture. Rather, it had a proper mass of 1.38 $M_\odot$ at the time of collapse (Nomoto 1987). A few other studies have been done of collapsing degenerate cores of 1.4 $M_\odot$. C/O cores were investigated by Baron et al. (1987b), Woosley & Baron (1992), and Colgate, Fryer, & Hand (1997) and O/Ne/Mg cores by Baron et al. (1987a) and Wilson & Mayle (1988),

In the calculation of Hillebrandt, Nomoto, & Wolff (1984), the burning of oxygen is found to appreciably alter the velocity and entropy of the infall. In these calculations, a prompt explosion occurred, ejecting the portion of the core beyond the standing oxygen-burning front, ~ 0.2 $M_\odot$. This prompt shock ultimately determined the entropy of the ejecta which was about 15 in units of k, the Boltzmann constant, for the mass shells of interest here. The electron fraction is rather low in the center of the core during the collapse, with a value of $Y_e \sim 0.36$ due to the preceding electron captures. This has some effect on the formation of the neutron star, but cannot directly affect the nucleosynthesis since this matter will remain in the core of the neutron star. Rather, Hillebrandt et al. note, the inner 0.02 $M_\odot$ of ejecta that do escape have neutron to proton ratios of 4 to 5 and hence $Y_e \sim 0.16 - 0.2$.

These very low values of Y_e are extreme by most current considerations of core collapse and r-process models, but they do arise rather naturally in the specific context of prompt explosions in collapsing O/Ne/Mg. The reason for this is simple. Because of the steep density gradient at the outer edge of the core, some mass ejection from there is likely, provided the core-bounce shock is sufficiently strong. This matter has been at high densities, but because of neutrino phase-space blocking Y_e remains moderately high until the mass shells pass through the neutrino sphere. At this stage, fast deleptonization sets in and produces the low electron fractions found by Hillebrandt, Nomoto, & Wolff. We note that this mechanism for producing very neutron-rich ejecta is rather independent of the actual explosion energy but only requires that some core material is ejected at all. Woosley & Baron (1992) argued that neutrino capture above the neutrinosphere will tend to raise the value of Y_e. This is a very model-dependent process, but deserves more study.

The other calculations of collapsing degenerate cores have been summarized by Colgate, Fryer, & Hand (1997), who conclude that the results depend rather sensitively on neutrino source terms and the equation of state. Colgate et al. conclude that all similar models, including their own that invoke the Baron, Cooperstein, & Kahana equation of state (e.g. Baron et al 1987a,b; Woosely & Baron 1992) fail to get a prompt explosion. The calculation of Colgate et al. using a Lattimer-Swesty equation of state (Lattimer & Swesty 1991) did yield an explosion with 0.08 - 0.2 $M_\odot$ ejected, very similar to the results of Hillebrandt, Nomoto, & Wolff who used an equation of state similar to that of Lattimer and Swesty. The issue of explosions in these cores seems to be, at least, open. Colgate et al. raise a concern with the overproduction of elements such as ^{88}Sr in the neutron-rich ejecta, but this may be suppressed in favor of the r-process elements at the very low values of Y_e suggested here.

The issue for now is whether the collapsing O/Ne/Mg cores of stars of 8-10 $M_\odot$ might make reasonable candidates for the r-process in a prompt explosion or in the subsequent

ν-driven wind.

3. The r-Process

Considerations of the systematics of the r-process have been considerably enhanced by parameter studies of the conditions necessary to produce the r-process. In particular, the work of Qian & Woosley (1996) and of Hoffman, Woosley, & Qian (1997) giving analytic and numerical models of the ν-driven wind process in terms of basic parameters of collapse calculations has provided important new tools to explore various scenarios, including the one we propose here. Hoffman et al. have explored a range of parameters for the entropy, S, the electron fraction Y_e, the dynamic timenscale, and, for the ν-driven wind process, the mass-loss rate. Qian & Woosley have given analytic estimates of the entropy, mass-loss rate, net neutrino heating, dynamical time scale, and final electron fraction as a function of neutron star mass, radius, neutrino luminosity and neutrino mean energy. The r-process parameters predicted in the prompt explosion of Hillebrandt, Nomoto, & Wolff (1984) occupy an extreme in low S and low Y_e in the study of Hoffman et al. This regime is close to that in classic studies of the r-process (Seeger, Fowler, & Clayton 1965; Hillebrandt, Takahashi, & Kodama 1976).

The analytic models of Hoffman et al. show an interesting feature that is certainly relevant to the scenario we explore here and may be relevant to the r-process in general. They contain a critical point at the value of Y_e that corresponds to the ratio $\bar{Z}/\mathrm{A}$ where $\bar{Z}$ is the mean atomic weight of the initial seed nucleus and A is the atomic weight of the target nucleus. For instance, the denominator of equation 19a of Hoffman et al. blows up for $Y_e = \bar{Z}/\mathrm{A}$, formally giving $S = 0$. This criterion on Y_e is equivalent to stipulating that the final mass fraction of α-particles is zero and that the initial composition distribution contains precisely the right fraction of α-particles and neutrons so that they are just used up as the target nucleus is formed. The critical point in the expressions of Hoffman et al. should not be taken literally, but it serves as a reminder that a choice of the right initial conditions helps to make the final product more easily (Seeger, Fowler & Clayton 1965). This may suggest that nature is looking for an r-process mechanism for which the initial value of Y_e is nearly equal to the "target" value of $\bar{Z}/A$.

More generally, the entropy required to make platinum is a sensitive function of Y_e for low values of Y_e. From equation 19a of Hoffman et al. we find that for a low $Y_e \sim 0.2$ and a dynamical time scale $t_{dyn,-3} \sim 0.5$ in units of 10^{-3}s for the prompt explosion of Hillebrandt et al. that

$$S = 200 t_{dyn,-3}^{1/3} (Y_{e,i} - \bar{Z}/A)^{2/3}. \tag{1}$$

For $\bar{Z} = 34$ and A = 190, or $\bar{Z}/A = 0.17$, equation 1 gives S =30 for $Y_{e,i} = 0.2$ and S = 15, the value predicted for the prompt explosion of the model of Hillebrandt et al., for $Y_{e,i} = 0.19$. Note that this model (and equation 19a from which it was derived) cannot handle the case of $Y_{e,i} = 0.16$, which is in the range quoted by Hillebrandt et al. These considerations suggest that the sort of collapse predicted by Hillebrandt et al. is a qualitatively viable candidate for the r-process and should be examined more rigorously.

Whether in such a model the envelope is ejected in a prompt shock or the shock stalls, neutrino emission from the newly-born cooling neutron star will drive a wind similar to what has been found in case of collapsing iron cores. Such a wind, lasting for several seconds, will also blow off the outer layers of the proto-neutron star even if the shock stalls, as it will for more massive stars. Because the neutron stars formed in this process are significantly different in several ways, one expects the r-process in the associated ν-driven wind to be quantitatively different than that previously considered. It is beyond the scope of this Letter to explore this subject in any detail and indeed many of the relevant parameters are not readily available. We will just take note of some qualitative effects with the aid of the analytic models of Qian & Woosley (1996).

Qian & Woosley show that the final entropy expected in a ν-driven wind is not very sensitive to the key parameters. It depends linearly on the neutron star mass, M, and on the radius of the neutron star as $\mathrm{R}^{-2/3}$, provided mean neutrino luminosity and energy remain unchanged. A lower mass neutron star will have a somewhat larger radius, so these factors will both decrease somewhat as a result of decreasing the mass of the neutron star. The expected increase in the radius, of order 30 to 50 percent, is within the current uncertainties of estimates of neutron star radii for different equations of state. The effect will, in any case, not be large. The assumption on which this conclusion rests, namely that less massive neutron stars will radiate neutrinos with essentially the same mean energy, is less certain. It may well be that for low-mass neutron stars with more extended surface layers, the mean neutrino energy is lower than for more massive ones, again reducing the final entropy somewhat. The most likely change in the final entropy will be a small reduction, probably by less than a factor of 2.

The mass-loss rate in the wind scales more sensitively with all the parameters, going as ${L_\nu}^{5/3}{\epsilon_{\bar{\nu}_e}}^{10/3}\ \mathrm{M}^{-2}\mathrm{R}^{5/3}$. The net neutrino heating also depends rather sensitively on these parameters, going as ${L_\nu}^{5/3}{\epsilon_{\bar{\nu}_e}}^{10/3}\mathrm{M}^{-2}\mathrm{R}^{2/3}$. The dynamical time scale goes as ${L_\nu}^{-1}{\epsilon_{\bar{\nu}_e}}^{-2}\mathrm{M}\mathrm{R}^{-1}$. The final value of Y_e will be that at the last achievable NSE value (Qian & Woosley 1996) and will also depend on these parameters in a way that must be determined.

The expectation is, to first order, that the neutrino luminosity will not be substantially different for the lower mass neutron stars we consider here. Because the binding energy to be liberated is less by about 50 percent, the same neutrino luminosity would imply a shorter Kelvin-Helmholtz cooling time. The shorter cooling time coupled with the lower entropy and mean neutrino energies would tend to work against the r-process in a ν-driven wind, but we do not know the difference between the ν_e and $\bar{\nu}_e$ energies, which determines the final electron fraction. The steeper density jump at the interface between the neutron star surface and the outer envelope might give a larger entropy from the start and thus a more effective r-process in the wind. These effects will tend to balance each other, and the r-process in the ν-driven wind may be similar for massive stars and those considered here.

4. Conclusions

We have shown that a convergence of arguments points to the collapsing O/Ne/Mg cores of stars in the mass range 8 to 10 $M_{\odot}$ as a promising site of the r-process. This mass range should produce neutron stars by core collapse and has been generally understudied to this point. The progenitor evolution is quite complex with multiple shell flashes and active electron capture. The collapse is expected to be quantitatively if not qualitatively different than for iron cores.

If these collapses produce an explosion of the kind found by Hillebrandt, Nomoto, & Wolff (1984), then this explosion with a rather low value of the initial electron fraction could produce a substantial r-process with the entropies predicted in the model. If the neutrino luminosity and mean neutrino energy are not too different from those obtained for collapsing iron cores, then the differences in the parameters determining the subsequent ν-driven wind r-process may not be radically different for the collapsing O/Ne/Mg cores. This may mean that all ν-driven wind processes can contribute substantially to the first and second r-process peak, but that a special characteristic of the low mass cores, e.g. a prompt explosion, may give the bulk of the third peak. Alternatively, these low-mass supernovae explosions could be responsible for the production of all of the r-process elements above Z=55.

A possible objection to this scenario arises from the observed propensity of neutron stars, at least those in binary systems where their mass can be measured, to cluster closely around a gravitational mass of 1.4 $M_{\odot}$. Their proper mass must be somewhat larger. This requires some special circumstances if this homogeneity is to be taken literally. We note that the sample of neutron stars with measured masses is small and that neutron stars that arise from collapsing O/Ne/Mg cores may be a relatively small fraction of all neutron stars. Unless one believes that all stars from 8 to 10 $M_{\odot}$ lose their envelopes and that their cores never collapse, these stars must produce neutron stars. We acknowledge that no such neutron star has ever been directly recognized, but feel that these stars are such a fruitful and overlooked site for the r-process that it is worth giving them closer scrutiny.

The observational indication that neutron stars originating from this mass range are rare may support our case. To estimate the total contribution of a given class of models to the Galactic r-process, one must have some idea of the event rate. For a Salpeter mass function, stars from 8 to 10 $M_{\odot}$ represent a fairly large fraction of all stars with mass in excess of 8 $M_{\odot}$, of order 0.3. For a somewhat steeper Miller-Scalo mass function, this fraction would be somewhat higher. Estimates of the r-process give an ejecta mass of order 10^{-4} $M_{\odot}$ per event for all supernovae (Hoffman, Woosley, & Qian 1997). If collapsing O/Ne/Mg cores were to eject 0.02 $M_{\odot}$ of r-process elements per event (neglecting for the moment a subsequent ν-driven wind) and they represent over 10 percent of all supernovae, then there is a strong possibility of overproducing the r-process. This is a liability in some way, but also gives ample room for inefficiency.

One obvious source of inefficiency is related to the question of envelope loss. A radiative wind or "superwind" operating at $\sim 10^{-4}$ $M_{\odot}$ yr^{-1} could remove the whole envelope and teminate the growth of the degenerate core before collapse ensues (García-Berro, Ritossa, & Iben 1997: and references therein). The systematics of this mass loss from stars of 8 - 10 $M_{\odot}$ are unknown and worth futher study. Another source of inefficiency is in the collapse calculations themselves. The calculations of Hillebrandt et al. under-resolved the outer layers of the core and so the mass ejected with very low Y_e was probably too high. Moreover, they did not include the effects of thermal neutrino losses, which would weaken the prompt shock, thereby also reducing the mass ejected. Finally, an equation of state was used which also favored prompt mass ejection. In conclusion, the amount of low Y_e material ejected from the collapsed O/Ne/Mg core could in reality be considerably less than was found by Hillebrandt et al. We note, however, that if prompt explosions were to occur in all supernovae and to produce the *r*-process, there would be a definite problem with overproduction (Hillebrandt 1978; Mathews & Ward 1985). This is another argument for producing the *r*-process in only a special category of supernovae, and some collapsing O/Ne/Mg cores might resemble such a class.

The primary conclusion of this study is that the evolution and collapse of cores of stars of 8 to 10 $M_\odot$ and the associated *r*-process deserves much greater quantitative study.

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