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Nucleosynthesis in O-Ne-Mg Supernovae

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ABSTRACT

We have studied detailed nucleosynthesis in the shocked surface layers of an oxygen-neon-magnesium core collapse supernova with an eye to determining wether the conditions are suitable for $r-$process nucleosynthesis. We find no such conditions in an unmodified model, but do find overproduction of N=50 nuclei (previously seen in early neutron-rich neutrino winds) in amounts that, if ejected, would pose serious problems for Galactic chemical evolution.

Subject headings: supernovae: general, nuclear reactions, nucleosynthesis, abundances

1. INTRODUCTION

The site of the $r-$process has been the most enduring mystery in nucleosynthesis theory since the publication of the seminal papers in this field (Cameron 1957; Burbidge et al. 1957). Of particular promise (in their times and for some even today) have been the many efforts suggesting Type II supernovae as the site with the relevant conditions arising either in or near the exploding core (initially championed by Burbidge et al. (1957)), with recent attention focused on aspects of neutrino interactions (Woosley & Hoffman 1992; Woosley et al. 1994), or in the outer layers (Thielemann et. al. 1979; Cowan et. al. 1982; Epstein, Colgate, & Haxton 1988).

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The requisite conditions for $r-$process nucleosynthesis in explosive scenarios with material freezing out from nuclear statistical equilibrium (NSE) have been derived with the general understanding that particular combinations of three parameters, the entropy, electron fraction (Y_e), and expansion timescale, give rise to specific features of the solar $r-$abundance pattern (Qian & Woosley 1996). As the wind evolves these parameters must sweep out a range of conditions that produce the many features of the solar $r-$process abundances, particularly the relative heights of the second and third peaks (Woosley et al. 1994). Recent models of core collapse still fall short of the necessary conditions to explain all the abundance features of the solar $r-$process, especially the high mass ($A \geq 130$) component (Hoffman, Woosley, & Qian 1997).

A site that has received recent interest involves explosions of O-Ne-Mg cores in $8-10\mathrm{M}_{\odot}$ supernovae. Successful SN explosions from such systems have been the subject of much debate (Wheeler, Cowan, & Hillebrandt 1998), some efforts found prompt explosions (Hillebrant, Nomoto, & Wolff 1984; Nomoto 1984), others did not (Burrows & Lattimer 1985), with the former now being completely ruled out with the advent of modern treatments of neutrino transport. Appeals to late-time neutrino heating have also been suggested (Mayle & Wilson 1988). It should be noted that nearly every attempt has used a common progenitor model (Nomoto 1984).

Recent efforts to revive the idea of a low-Y_e, low-entropy scenario for $r-$processing have included detailed nucleosynthesis calculations (Wanajo et. al. 2005; Ning, Qian, & Meyer 2007). In the former case, an unmodified SN model (computed without neutrino transport) provides a very low explosion energy ($E_{exp} \sim 0.02$ B), with modestly neutron rich conditions ($Y_{e,min} = 0.45$) and no $r-$process. To obtain it they artificially increased the shock heating term to obtain larger explosions (~ 1 B) and lower electron fractions ($0.14 \leq Y_{e,min} \leq 0.36$) and suggest material experiencing these conditions must be ejected to explain the principle $r-$process features.

By contrast, Ning, Qian, & Meyer (2007) propose that the necessary conditions arise in the shocked C-O layers above the O-Ne-Mg core at the location of a very steep density gradient near the edge of the mass cut in these compact stars. This allows for rapid shock wave passage accompanied by high peak temperatures, giving rise to a short expansion timescale. Such a combination has been suggested as a viable $r-$process scenario even at modest entropy with a neutron excess near zero (Jordan & Meyer 2004). As with the neutrino wind scenario, this production would be primary. Ning et. al. appeal to this scenario to help bolster observational suggestions that $r-$process nuclei with A ≥ 130 are preferentially associated with a low mass SN component (Ishimaru et. al. 2004; Qian & Wasserburg 2007).

Although the initial conditions of Ning, Qian, & Meyer (2007) were taken from a stellar evolution model (Nomoto 1984, 1987), the evolution of temperature and density in the mass-shell trajectories was derived in a semianalytical fashion assuming a shock speed in the region of interest approaching 10^{10} cm s^{-1}. Using shock jump relations (Matzner & Mckee 1999), they derived the entropy and expansion timescale and obtained resulting nucleosynthesis that did exhibit characteristics reminiscent of $r-$process abundances. The authors conclude by imploring further research to test their assertions in modern finely zoned supernova explosion simulations of progenitors in the same mass range.

Recently, Kitaura, Janka, & Hillebrandt (2006) have calculated supernovae explosions in this mass range, considering an 8.8 $M_{\odot}$ progenitor star with an O-Ne-Mg core (Nomoto 1984) and using a sophisticated treatment of neutrino transport. The nucleosynthesis studies presented here are based on an update of these (spherically symmetric) simulations for a revised progenitor model, in which the outer layers of the helium shell and a dilute hydrogen envelope were added (K. Nomoto 2006, private communication). The new simulations also include an improved treatment of electron captures and inelastic neutrino scattering by nuclei in NSE (Langanke et. al. 2003, 2007). The principle results of these simulations will be discussed in a separate publication (Janka et. al. 2007).

2. Nucleosynthesis in an exploding 8.8 $M_{\odot}$ Star

Our results survey explosive nucleosynthesis in 32 zones extracted from an 8.8 $M_{\odot}$ SN model starting at the edge of the O-Ne-Mg core and extending through the C-O and He layers. The mass cut that defined our inner most zone had an initial (pre-collapse) radius of 7.717×10^7 cm with an enclosed mass of 1.363 $M_{\odot}$. The last zone studied had a radius at the onset of core collapse of 1.1306×10^8 cm with an enclosed mass of 1.376 $M_{\odot}$. The amount of processed ejecta is 0.013 $M_{\odot}$. Exterior to this was a hydrogen envelope (70% H, 30% He) whose outermost zone at core collapse was at radius 6.414×10^{13} cm with an enclosed mass of 2.626 $M_{\odot}$. The amount to total ejecta is the difference, 1.263 $M_{\odot}$.

During shock wave passage, the temperature increased dramatically and in most of the zones exceeded $T_9 = 7$. As such photo-disintegration will disassemble any C or O into $\alpha-$particles and nucleons. Each nucleosynthesis calculation started at a point in the expansion when the temperature had declined to $T_9 = 9.0$ (or its maximum value if it never achieved this), with the starting values of density and Y_e also taken from the SN model, and followed until the temperature declined to $T_9 = 0.1$ (or the minimum value achieved in the SN model trajectory, in a few cases as high as $T_9 = 0.5$). Initial compositions for zones with an initial $Y_e \leq 0.5$ were assumed to be α-particles and free neutrons, otherwise free neutrons and protons. Since nucleosynthesis beyond the iron group requires particle capture on seed nuclei that here must be built up by NSE, we define a simple expansion timescale (in seconds) as the time for the temperature to decline from $T_9 = 5.0$ (or its highest value attained) to $1/e$ of this value. See Table 1 for the initial conditions.

Neutrino induced reactions for free nucleons and $\alpha-$particles were included in all calculations (McLaughlin & Fuller 1995, 1996). As reported by Ning, Qian, & Meyer (2007), the inclusion of neutrino reactions was not crucial to the final results of what is here essentially explosive nucleosynthesis.

2.1. Results

Figure 1 shows the mass-weighted production factors normalized to the total amount of ejecta given by

$$P(i) = \sum_j \frac{M_j}{M^{\mathrm{ej}}} \frac{X_j(i)}{X_{\odot,i}}. \tag{1}$$

In this equation, the sum is over all 32 trajectories, $X_j(i)$ is the mass fraction of nuclide i in the jth trajectory, $X_{\odot,i}$ is the mass fraction of nuclide i in the Sun (Lodders 2003), M_j is the mass of the jth trajectory, and $M^{\mathrm{ej}} = 1.263\ \mathrm{M}_\odot$ is the total mass ejected in the SN explosion whose energy was ~ 0.1 B (~ 0.2 B in a corresponding 2D simulation).

We see no evidence of an $r-$process for the starting entropy and Y_e conditions given in the model of Müller & Janka (2007) principally because the expansion timescales of the trajectories containing the most mass are long (~ 0.01 s) and the entropies are small ($\sim 10-20$, see Table 1). By contrast the same quantities derived by Ning, Qian, & Meyer (2007) were entropy = 139 k_b/nucleon, and an expansion timescale to $e-$fold from $T_9 = 5.0$ of 0.0013 sec. The explosion energy agrees with model Q3 of Wanajo et. al. (2005), but the Y_e range is more neutron-rich in the zones that dominated the nucleosynthesis.

We do note production of species above the iron group, but they terminate for nuclei in the N=50 closed shell. Attractive combinations of expansion timescale and entropy (for the given Y_e) do appear to be achieved for the trajectories farthest out, but these exhibit a rapidly diminishing drop in the peak shock temperature and density (the last two trajectories are in the extended hydrogen envelope, hence they have $Y_e > 0.5$, and they never reach NSE). In every calculation the free nucleons were all consumed in the build up of intermediate-mass nuclei during the α-rich freezeout. See Table 1 for the final $\alpha-$particle mass fraction in each zone and the largest mass weighted production factor.

Indeed, the nucleosynthesis here is dominated by trajectories 7-12 which all exhibit fairly long expansion timescales, entropies near 18, and initial values of $Y_e \leq 0.48$. Between them they constitute 40% of the total ejecta studied. The production of the dominant N=50 isotopes (^{90}Zr in particular) is most pronounced in zones 9 and 10. All of the co-produced species (those made within a factor of ~ 4 of the largest production factor) are made as themselves with the dominant reaction flows occurring in the valley of stability.

This result is reminiscent of nucleosynthesis seen at early times in the neutrino-driven wind of more traditional SNe II (Witti, Janka, & Takahashi 1993; Woosley et al. 1994), where an overproduction of N=50 isotopes presented problems for a model that at late times produced a high-entropy solution favorable to the $r-$process. The problem here may not appear so striking, in that ^{90}Zr is also made with ^{74}Se, but both are made at a very high production factor. Both ^{70}Ge and ^{90}Zr anchor two quasi-equilibrium clusters near the iron group and N=50, and their abundances determine the production of ^{74}Se and ^{92}Mo, respectively. The other two light $p-$nuclei in between, ^{78}Kr and ^{84}Sr, are not members of these quasi-equilibrium clusters and owe their production to nuclear flows between them (Hoffman et al. 1996). The dominant species (by mass fraction) for trajectory 7 ($Y_e = 0.47$, which made the most ^{92}Mo) are ^{66}Zn and ^{60,62}Ni (all at 20% by mass fraction), and ^{90}Zr, ^{64}Zn, and ^{70}Ge (all $\sim 5\%$). As here, Hoffman et al. (1996) also saw limited production of the heavier $p-$nuclei ^{94}Mo, ^{96}Ru and ^{98}Ru, which are made in equilibrium with ^{90}Zr but always at a level smaller than that for ^{92}Mo. The N=50 nucleosynthesis can be eliminated in preference to light $p-$nuclei if Y_e is constrained to be in a narrow range (~ 0.485). In the SN model of Woosley et al. (1994), the N=50 overproduction problem persisted if the amount of material that experienced $Y_e \leq 0.47$ was greater than 10^{-4}M$_\odot$. Here it is even worse (see below).

Interestingly, the recently developed $\nu p-$process does co-produce the full range of light $p-$nuclei from ^{74}Se to ^{102}Pd, especially ^{94}Mo, ^{96}Ru and ^{98}Ru, in quantities that could for the first time explain their solar abundances in early proton-rich neutrino wind models (Pruet et. al. 2006; Fröhlich et. al. 2006), but they fail to adequately co-produce ^{92}Mo. Details of the nuclear physics uncertainties affecting the reaction flows that determine the solar ratio for ^{92}Mo and ^{94}Mo have recently been explored (Fisker, Hoffman, & Pruet 2007). Within current uncertainties in the proton-separation energies of $^{91-93}$Rh, they suggest this ratio could be achieved along with co-production of all the light $p-$ nuclei between Sr and Pd in the $\nu p-$process if $S_p(^{93}\mathrm{Rh}) = 1.64 \pm 0.1$ MeV.

2.2. Discussion

If ejected, the values of the largest normalized production factors in these zones ($\sim$ 1000) would cause serious problems for Galactic chemical evolution. Considering the largest production factor (^{90}Zr), the enrichment by a single event relative to solar would be

$$\left[\frac{Zr}{H}\right]_{single} = log\left(\frac{Y_{Zr}/M_{mix}}{X_{\odot}(Zr)}\right) \tag{2}$$

where $Y_{Zr} = \sum_j X_j(Zr) \times M_j$ is the mass yield of ^{90}Zr ($1.75 \times 10^{-4} M_{\odot}$ for the sum of zones 7-12 where ^{90}Zr is produced with a mass fraction grater than 10^{-4}), M_{mix} is the mass of ISM into which the ejecta of this single event mixes ($\sim 3000 M_{\odot}$, Thornton et. al. (1998)), and $X_{\odot}$ is the mass fraction of ^{90}Zr in the Sun (1.53×10^{-8}, Lodders (2003)). This is equivalent to the definition of the production factor (Eq. 1) with $M^{\rm ej}$ replaced by M_{mix}. For ^{90}Zr, the enrichment is 3.8, *i.e.* nearly 4 times solar, implying a very rare event.

If M_{mix} is typical of the mass that can be contaminated by such a SN and assuming one occurred at most once at some average location over the age of the Galaxy then the frequency f_{SN} for it to occur is given by

$$N_{expected} \sim \frac{f_{SN} M_{mix} t_{Gal}}{M_{gas}} = 1 \tag{3}$$

where $M_{gas} \sim 10^{10} M_{\odot}$ is the mass of the gas in the Galaxy, and $t_{Gal} \sim 10^{10}$ yr its age, giving a frequency of once every 3000 years. This is in disagreement with recent best estimates that suggest explosions of O-Ne-Mg cores comprise 4% of all core-collapse events (Poelarends et. al. 2007), which translates (assuming a present day upper limit of two SNe II per century) to 0.0008 yr^{-1}. If one appeals to their firm upper limit of 20% (based on the many uncertainties in modeling the progenitors), then this rate could rise to 0.004 yr^{-1}.

Over the history of the Galaxy, this enrichment is

$$\left[\frac{Zr}{H}\right]_{all} = log\left[\frac{Y_{Zr} f_{SN} t_{Gal}}{M_{gas}} / X_{\odot}(Zr)\right] \tag{4}$$

which gives 10-50 times the solar value. We note that both M_{gas} and f_{SN} may have been different in the past, but the ratio of the two which is the rate of SN per unit mass of gas may vary much less as the SN progenitor formation rate is proportional to the gas available.

3. Conclusions

We have studied in detail the nucleosynthesis in the shocked outer layers of an O-Ne-Mg Type II SN to test the assertion that this might be a viable site for the $r-$process. While Ning, Qian, & Meyer (2007) derived shock conditions from the same progenitor model we use (Nomoto (1984) plus the recent supplementation with a hydrogen envelope) in a semi-analytic manner with an *assumed* shock velocity, our conditions arise from a detailed explosion simulation (Janka et. al. 2007). We find conditions for nucleosynthesis that are very different from those of Ning, Qian, & Meyer (2007), especially in regards to peak temperatures and expansion timescales. Consequently we cannot support their assertion that this is a potential site for the $r-$process as we see neither the requisite conditions nor products. Our results are however very reminiscent of previous calculations studying nucleosynthesis in the neutrino-driven wind (Woosley et al. 1994; Hoffman et al. 1996).

The combination of low entropies (~ 20) and electron fractions ($Y_e \leq 0.47$) in $5.5 \times 10^{-3} M_\odot$ of ejecta from our model suggest that this one event would produce nearly 4 times the solar abundance of ^{90}Zr. This is unlikely, as observations of Zr are well established in metal-poor stars where enrichment to this level has not been seen. If this represents a very rare event, it leaves little room for the production of Zr from other sources (such as the neutrino winds of ordinary SNe II, and still less for the $s-$process). But the initial mass function suggests there are many stars with masses between 8 and 10 $M_\odot$, and recent studies indicate that 4% of these should end their lives as SNe II (Poelarends et. al. 2007). We are therefore forced to consider that this is not a typical event (or even a very rare one) and that some aspect of the progenitor model, the explosion model, or the nuclear physics used in determining the nucleosynthesis is grossly in error.

On the later point, since the reaction flows producing the abundant species move along the valley of stability, we feel confident that the ingredients that went into the calculation of the nuclear reaction cross sections and the particle separation energies (so important in QSE) are on firm ground (Rauscher & Thielemann 2000). There is no complication due to neutrino nucleosynthesis as the radii of the zones considered, hundreds of kilometers, are too large for a substantial neutrino fluence.

On the stellar modeling side our explosion model is based on a very modern treatment (Kitaura, Janka, & Hillebrandt 2006; Janka et. al. 2007), with issues of fallback being negligible. The explosion simulation employed here was spherically symmetric, but a corresponding two-dimensional (axisymmetric) model including the effects of convection shows the same nucleosynthesis-relevant features (for details, see Janka et al. 2007). This leaves the pre-SN model, which was originally calculated as a helium-core with a hydrogen-envelope subsequently added to it. There are numerous difficulties in accurately calculating the pre-SN structure, including thermal pulses of the unstable He shell source, mass loss, and dredge-up, to name a few (Poelarends et. al. 2007). The effects of rotation and magnetic fields might also play a non-negligible role during stellar evolution and collapse. We therefore view the pre-SN model as the most pertinent area where research should be focused towards understanding this important class of stars and consider such investigations necessary to address the assertion that they can serve as crucibles for half the species above iron.

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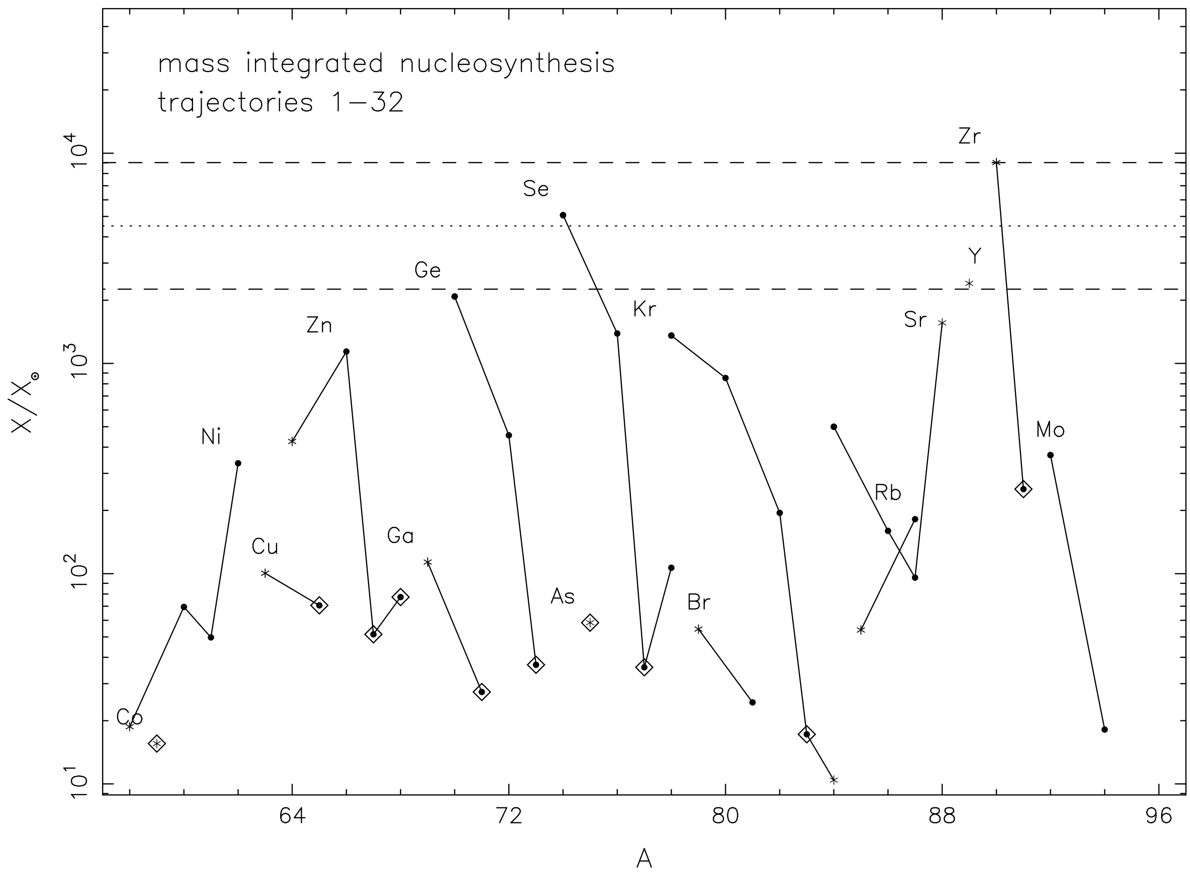

Fig. 1.— Mass weighted production factors characterizing the integrated nucleosynthesis in all 32 zones studied. Nuclides of a given element are connected by solid lines, a diamond surrounding the data point indicates production chiefly by a radioactive progenitor. The horizontal lines represent a band of co-production for nuclei made within a factor of two and four of ^{90}Zr.

Table 1. Outflow Characteristics

traj.[a]	r_7	T_9	s/k_b	Y_e	$\tau_{\rm exp}(s)$	Mass[b]	X(α)[c]	$^{A}Z_{P_{\rm max}}$	$P_{\rm max}$
1	1.08	9.2	30	.53	.046	5.00	.74	^{45}Sc	2.95
2	1.09	9.5	29	.52	.051	5.00	.72	^{45}Sc	1.98
3	1.23	9.0	27	.51	.058	10.00	.67	^{49}Ti	3.44
4	1.32	9.1	25	.50	.064	10.00	.59	^{62}Ni	2.04
5	1.47	9.1	24	.50	.073	10.00	.55	^{62}Ni	7.05
6	2.14	9.0	21	.48	.092	5.00	.38	^{64}Zn	45.53
7	2.27	9.1	20	.47	.100	5.00	.28	^{74}Se	1001.58
8	2.40	9.0	19	.47	.107	5.00	.17	^{74}Se	843.23
9	2.46	9.1	18	.46	.114	15.00	.12	^{90}Zr	4928.74
10	2.67	9.1	16	.45	.118	15.00	.04	^{90}Zr	2589.07
11	2.76	9.1	14	.46	.112	5.00	.10	^{74}Se	629.45
12	2.79	9.0	14	.47	.109	10.00	.14	^{74}Se	1346.00
13	2.70	9.0	12	.48	.104	10.00	.21	^{64}Zn	60.97
14	2.68	9.2	11	.49	.099	10.00	.22	^{62}Ni	13.54
15	2.50	9.0	10	.50	.092	10.00	.23	^{62}Ni	4.68
16	2.40	9.0	10	.50	.067	6.00	.24	^{60}Ni	.82
17	2.32	9.0	10	.50	.038	1.00	.31	^{63}Cu	.29
18	2.37	9.1	13	.50	.032	1.00	.43	^{63}Cu	.43
19	2.66	8.0	14	.50	.025	1.00	.49	^{63}Cu	.49
20	2.90	7.1	15	.50	.017	.10	.58	^{63}Cu	.06
21	2.98	7.0	16	.50	.015	.10	.60	^{63}Cu	.06
22	3.00	6.6	16	.50	.014	.05	.62	^{63}Cu	.03
23	3.07	6.3	17	.50	.014	.05	.64	^{63}Cu	.03
24	3.09	5.8	20	.50	.013	.05	.40	^{63}Cu	.01
25	3.32	4.9	42	.50	.013	.05	.00	^{52}Cr	.00
26	3.74	4.3	53	.50	.013	.05	.00	^{40}Ca	.01
27	4.77	3.2	88	.50	.013	.01	.02	^{84}Sr	.05
28	5.24	2.8	108	.50	.013	.01	.00	^{41}K	.00
29	5.99	2.5	132	.50	.013	.01	.80	^{39}K	.00
30	6.50	2.3	146	.50	.012	.01	1.00	^{7}Li	.00
31	7.21	2.0	185	.84	.010	.01	.33	^{51}V	.00
32	9.07	1.4	381	.85	.006	.01	.30	^{2}H	.00

[a]Initial conditions at radius r_7 (in 10^7 cm) when $T_9 \sim 9.0$ (or its peak value).

[b]Mass of the zone in units of $10^{-4} M_\odot$. The mass interior to traj. 1 was 1.363 $M_\odot$.

[c]Final $\alpha-$particle mass fraction, the nucleus with the largest mass weighted production factor, and its value.