NUCLEOSYNTHESIS IN MASSIVE POPULATION II STARS

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1. INTRODUCTION

According to the conventional wisdom, the first stars formed in our Galaxy, including the massive ones responsible for most heavy element synthesis, must have had metal abundances much lower than solar. They may also have had somewhat lower helium abundances, corresponding to an enrichment $\Delta Y/\Delta Z = 2.7 \pm 1.0$ over the history of the Galaxy, a larger ratio than is readily accounted for by standard (Arnett-type) supernovae (Hacyan et al. 1977) or by mass shed from lower mass stars (Gingold 1977). But early nucleosynthesis must have occurred in stars with Pop II compositions. Several authors (Ezer and Cameron 1969; Cary 1974; Chiosi and Nasi 1974; Trimble et al. 1973) have modelled and evolved such stars, but none of the studies followed the stars far enough from the main sequence to be able to say anything very quantitative about their contribution to galactic chemical evolution. We address here the question of the effects of initial composition upon helium and heavy element production in massive stars.

2. THE CALCULATIONS

The stellar evolution code developed by Eggleton (1973) has been modified (Dearborn and Eggleton 1977) to apply to massive stars, incorporating the standard physics (nuclear reaction rates from Fowler et al. 1975; neutrino loss rates from Beaudet et al. 1967; opacities from Cox and Stewart 1970). Convective mixing was treated as a diffusion problem. By adjusting the rate of diffusion

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it was possible to examine the effects of semi convection. We evolved stars of 12 and 32 $M_\odot$ with three compositions (X=0.7, Z=0.02; X=0.7, Z=0.0004; X=0.78, Z=0.0004) representing Pop I and Pop II with high and low initial helium. Calculations were stopped early in carbon-burning. We can, therefore, say nothing about relative amounts of heavy elements, except C and O. The C/O ratio is quite sensitive to diffusion time scale, because every He nucleus that leaks into the CO core turns a previously formed C into an O. Thus the fact that we see lots of carbon in the Universe limits the amount by which semi convection can erode the helium supply prior to expulsion by a supernova event. Diffusion time scales probably cannot be much shorter than those used here (about 10^{-6} of the nuclear time scale). Thus we believe that the net change in masses of helium and heavy elements in our stars during their evolution should be realistic estimates of $\Delta Y/\Delta Z$ expelled by them as SN's.

The models and their net production of He and "metals" (mostly C and O in our models, but appreciable fractions of the core will burn to Ne, Mg, Si, Fe, etc. in late, very short-lived stages) are listed in Table I. The last column for each model is the expelled $\Delta Y/\Delta Z$ if a 1.4 $M_\odot$ remnant, made of heavy elements is left.

TABLE I

NET HELIUM AND HEAVY ELEMENT PRODUCTION BY STARS AS A FUNCTION OF MASS AND COMPOSITION. ALL MASS QUANTITIES ARE IN $M_\odot$.

M	X	Z	ΔY	ΔZ	$\Delta Y/\Delta Z$
12	0.7	0.02	0.9	1.8	2.24
12	0.7	0.0004	0.8	2.2	1.08
12	0.78	0.0004	1.0	1.9	1.96
32	0.7	0.02	2.0	9.3	0.26
32	0.7	0.0004	1.5	10.0	0.18
32	0.78	0.0004	3.4	8.3	0.49

3. IMPLICATIONS FOR GALACTIC CHEMICAL EVOLUTION

We explore here the consequences of varying two quantities that enter into calculations of galactic chemical evolution. These are initial stellar composition, as discussed above, and mass loss early in the lives of massive stars, as discussed by Dearborn and Eggleton (1977) and Dearborn *et al*. (1976a, 1976b). Our models are exceedingly simple. We assume that stars from 6 to 100 $M_\odot$ are formed according to a Salpeter birthrate function with $\alpha = 2.35$. All stars more massive than 6 $M_\odot$ give rise to supernovae that blow off everything but a 1.4 $M_\odot$ core. Mass loss, if it is important at all, acts to reduce the effective stellar masses that do the nucleosynthesis so as to steepen α to 3.49 or 4.97 above 15 $M_\odot$. This reduces the amount of mass in 100 $M_\odot$ stars relative to that in 15 $M_\odot$ stars by factors of 10 or 100. Finally, the Galaxy is assumed to be capable of making the heavy elements we see, so that the only interesting number for each model is $\Delta Y/\Delta Z$. Since stars below 6 $M_\odot$ are more likely to make He than heavy elements, our ratios are lower limits to what would actually be produced by a generation of stars with these compositions and mass losses. We give in Table II the values of $\Delta Y/\Delta Z$ for 9 models, have three initial compositions and three values of α for M greater than 15$M_\odot$. It is clear that initial composition can vary the production ratio by 50% either way and that significant mass loss can increase $\Delta Y/\Delta Z$ to values large enough to match any of the observations.

TABLE II

NET $\Delta Y/\Delta Z$ FOR A GENERATION OF STARS AS A FUNCTION OF COMPOSITION AND IMPORTANCE OF MASS LOSS.

X/Z	no mass loss	moderate	extreme
0.7/0.02	0.44	2.87	3.34
0.7/0.0004	0.32	2.02	2.30
0.78/0.0004	0.60	2.82	3.27

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DISCUSSION

TINSLEY: How much does your mass loss change the mass function of stars between formation and death? Is it enough to affect the estimates Arnett makes of the relative amounts of different "Z" elements shed per generation of stars?

TRIMBLE: Our "moderate" mass loss essentially eliminates all stars more massive than 30 $M_\odot$, in accordance with the observed absence of very massive M supergiants. This would affect Arnett's nucleosynthesis, but not disasterously, in the sense that he can make all the elements we need using masses up to about 22 $M_\odot$. Our "extreme" mass loss eliminates most stars above 15 or 20 $M_\odot$ and is probably not in the realm of practical politics for making the heavy elements.

CAYREL de STROBEL: Your results for $\Delta Y/\Delta Z$ are very nice, because they resemble closely our observational results about a simultaneous variation of the helium content with the metal content (see papers in Part VII) for older disk stars. The fact that you get these results theoretically and we get them observationally gives us confidence that they are real.

CHIOSI: I would like to know more about how mass loss is included in your computations. I wonder whether your evolutionary models for this range of mass, with the mass loss rates you seem to adopt, are able to reproduce the observed features of the HR diagram of supergiant stars.

I have the feeling that the results by Eggleton and Dearborn (1977) are obtained by using mass-loss rates too high for initial masses of $\sim$ 30 $M_\odot$ on the main sequence, in that they are not supported by the observational information on mass flow in OB stars.

TRIMBLE: This problem has enough free parameters in initial mass function, initial composition, choice of mixing length, and treatment of semi convection, as well as rate and duration of mass loss, that it should be possible to fit an elephant, let alone any observed HR diagram one wants.

We, in fact, put all the mass loss during hydrogen burning, so that the denuded star merely mocks one of lower initial mass in its nucleosynthetic properties. The total amount of mass lost in the "extreme" case is consistent with the work of Eggleton and Dearborn (1977) and may well be too high. Our "intermediate" case is perhaps more realistic.