SUPERGIANT MASS LOSS AND THE CASSIOPEIA A PROGENITOR

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Observations of the chemical abundances in young supernova remnants may be used, in some circumstances, to place constraints on the evolution of the progenitor stars. For example, if a progenitor was massive ($M > 10\ M_\odot$), the presence of high $^{14}N/^{1}H$ ratios (that is, more than five time the solar value) in the supernova remnant can imply that substantial mass loss took place during the star's early evolution, that is, while it was an early-type supergiant.

An example is the supernova remnant Cassiopeia A, which has a non-solar composition and a $^{14}N/^{1}H$ ratio which is very large in some regions. A comparison of the observed abundances in Cas A with the abundances predicted from theoretical calculations of the evolution of massive stars indicates, firstly, that the progenitor star was massive and, secondly, that substantial mass loss took place while it was an early-type supergiant. The rate of mass loss required in this case is consistent with the rates observed in early-type supergiants.

I. INTRODUCTION

The observed chemical abundances in young supernova remnants can be used to place constraints on the masses and evolution of the progenitor stars. Detailed stellar evolutionary calculations have now been performed for a wide range of initial masses, and in some cases, the evolution has been followed through much of the stars' life. Although the composition in a supernova remnant is likely altered to some extent by the supernova explosion itself, there are circumstances in which a comparison between the compositions predicted by stellar evolution theory alone and those observed can be meaningful.

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Only the abundances in those supernova remnants that have swept up little interstellar material can be compared directly with stellar evolution theory, and very few such objects are known in our galaxy, Cas A and Kepler being the best examples. Perhaps the best studied remnant abundances are those in the Crab and the Cas A supernova remnants (see Davidson, 1978, and Chevalier and Kirshner, 1978). Arnett (1975) has explored some of the implications of these two supernova remnants for the nature of the progenitor stars. He compared his models for 4 $M_\odot$ and 8 $M_\odot$ 'helium cores', which correspond to stars with masses of approximately 15 $M_\odot$ and 25 $M_\odot$, respectively, with earlier abundance determinations for these objects by Davidson (1973) and by Peimbert (1971). He found, for example, that the abundances in some regions of the Cas A supernova remnant (namely, the "fast-moving knots") are consistent with the abundances obtained in his 8 $M_\odot$ 'helium core' model as it nears the end of its quasi-static evolution.

The Cas A supernova remnant is particularly interesting in that it has at least two distinct types of optically emitting regions. The 'fast moving knots' are observed to be traveling outwards from the center of the region at about 10^4 km/sec, whereas the 'quasi-stationary flocculi' have only a small outward velocity $\sim$ 150 km/sec superimposed on large random velocities (see Kamper and van den Bergh, 1976). The chemical compositions of these two types of emitting region are very distinct. The 'fast moving knots' have no observed hydrogen but are enhanced in oxygen and the burning products of oxygen, while the 'quasi-stationary flocculi' are overabundant in nitrogen and helium (see Chevalier and Kirshner, 1978).

It has previously been suggested that the material in the 'fast moving knots' was ejected from the stellar interior during the supernova explosion, and that the 'quasi-stationary flocculi' are formed from material that was shed from the surface of the star prior to the supernova explosion (see Peimbert and van den Bergh, 1971, and Chevalier, 1976). The dynamics of the 'quasi-stationary flocculi', as determined by Kamper and van den Bergh (1976), imply that the material was lost from the stellar surface at least 10^4 years ago.

The abundances in the 'fast moving knots' imply that the progenitor star had an initial mass of at least 9 $M_\odot$ and possibly was much more massive (see Arnett, 1975, Chevalier and Kirshner, 1978, and Lamb, 1978a).

Using these suggestions concerning the origin of the material in the Cas A remnant and the abundances as determined by Chevalier and Kirshner (1978), Lamb (1978a)

has constructed a consistent evolutionary picture for the Cas A progenitor star which involves two periods of mass loss, one while the star was an early-type supergiant (during its early evolution) and the other when the star was considerably more evolved.

The argument for mass loss while the progenitor was an early-type supergiant hinges on the high N/H ratios observed in the 'quasi-stationary flocculi', as is explained in Section II, where a comparison between this observed ratio and those predicted by evolutionary calculations of massive stars is presented. In Section III we estimate the required mass loss rates and compare them with those observed for early-type supergiants. Finally, in Section IV we give a brief summary of our conclusions.

II. THE EARLY EPISODE OF MASS LOSS

If the 'quasi-stationary flocculi' consist of material shed from the progenitor star prior to the supernova explosion, then one would expect their chemical composition to be very similar to that at the surface of the appropriate star at some phase in its evolution. Concentrating on the firmest abundance determinations for the 'quasi-stationary flocculi', which indicate that the N/H ratio is approximately 10 - 20 times the 'solar' value and that the He/H ratio is also approximately an order of magnitude larger than the 'solar' value (Chevalier and Kirshner, 1978), we find that at no time during the evolution of massive stars do such high relative abundances of nitrogen and helium appear at the stellar surface (see Lamb, Iben, and Howard, 1976), if there is no mass loss.

In massive stars of constant mass, 'non-solar' abundance ratios only appear at the surface once a convective envelope has formed. In the 15 $M_\odot$ stars of Endal (1975) and Lamb, Iben, and Howard (1976), this occurs near the end of core helium burning, as the star evolves to the red across the Hertzsprung gap. However, in the 25 $M_\odot$ model of Lamb et al., no convective envelope develops during the evolution through core-carbon burning. Even in the 15 $M_\odot$ model, the N/H ratio does not climb to more than five times the solar value in the convective envelope as the convection eats down into layers partially processed through core-hydrogen burning.

To find a region within a massive star where the nitrogen and helium abundances with respect to that of hydrogen are consistent with those found in the 'quasi-stationary flocculi' one must look further back in the

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evolution, to the period of core hydrogen burning, that is to the main sequence evolution. At this time deposits of hydrogen depleted material enriched in nitrogen and helium are laid down outside the contracting convective core (see Lamb, Iben, and Howard, 1976, and Lamb, 1978a).

An example of the composition profiles through a massive star at a time near the end of core-hydrogen burning is given in Figure 1, which shows a 50 $M_\odot$ star (Lamb, 1978b) with an initial composition of Y = 0.28 and Z = 0.02. In the region between $M_r \sim 32\ M_\odot$ and $M_r \sim 41\ M_\odot$, nitrogen and helium have been built up at the expense of carbon, oxygen, and hydrogen. As the evolution progresses, the abundances of nitrogen and helium in this region climb with respect to that of hydrogen, which continues to be depleted. Eventually the N/H ratio rises to approximately ten times the solar value in a region which expands inwards from $M_r \sim 41\ M_\odot$. (Analogous composition profiles for 15 $M_\odot$ and 25 $M_\odot$ stars are presented in Figures 1 and 2 of Lamb, 1978a, for a time shortly after the end of core-hydrogen burning; by this stage the N/H ratio has risen to approximately ten times the 'solar' value.) If this nitrogen and helium enriched material is to appear at the stellar surface undiluted by the overlying hydrogen envelope, this outer hydrogen layer must be shed from the star prior to the development of a convective envelope. This means that the mass loss epidsode must have taken place to the blue of the Hertzsprung gap, that is, at the time when the star was successively an O, B, and A type supergiant. In the next section we estimate the mass loss rates which are required to remove the outer hydrogen envelope in the available time and compare these with mass loss rates determined from observations of early-type supergiants.

III. MASS LOSS RATES

A comparison of the abundance profile for a 50 $M_\odot$ star with those for 15 $M_\odot$ and 25 $M_\odot$ stars (see Figures 1 and 2 of Lamb, 1978a) indicates that in all three stars the amount of material which must be shed from the stellar envelope to expose the nitrogen enriched material is approximately 9 $M_\odot$. Mean mass loss rates can be computed using the known times available for the mass loss. The relevant evolutionary time scales for the 15 $M_\odot$ and 25 $M_\odot$ stars are given in Lamb, Iben, and Howard (1976) and yield mean mass loss rates of $\sim 6 \times 10^{-7}\ M_\odot\ yr^{-1}$ and $\sim 1 \times 10^{-6}\ M_\odot\ yr^{-1}$, respectively. The time available to the 50 $M_\odot$ star to lose the 9 $M_\odot$ of material is approximately 4.5×10^6 years, which yields a mean loss rate of $\sim 2 \times 10^{-6}\ M_\odot\ yr^{-1}$.

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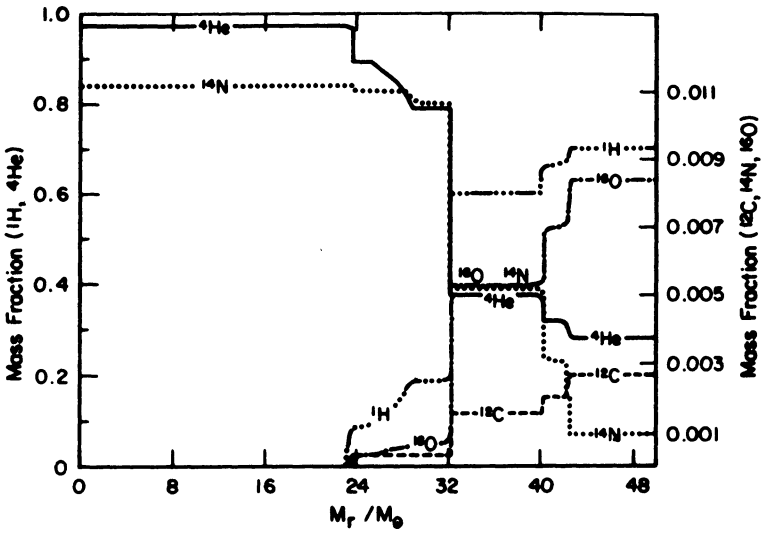

FIG. 1. - Compositional profiles within a 50 $M_\odot$ star near the end of core hydrogen burning. Abscissa, Lagrangian mass co-ordinate; ordinate, mass fraction.

These mass loss rates can be compared with those found observationally for early-type supergiants.

Estimates of mass loss rates for a large sample of O and B supergiants have been obtained optically by Hutchings (1976), who found a large spread in mass loss rates within his sample. For the region of the H-R diagram through which stars in the mass range 15 $M_\odot$ to 50 $M_\odot$ are likely to evolve, namely between $M_{bol} \sim -6.0$ and $M_{bol} \sim -9.5$, he found mass loss rates ranging from $< 10^{-7}$ $M_\odot$ yr^{-1} to $\sim 7 \times 10^{-6}$ $M_\odot$ yr^{-1}. In another study, Barlow and Cohen (1977) have obtained mass loss rates for a sample of O, B, and A supergiants using infrared observations of the stars together with a velocity law for the mass outflow from P Cygni. The latter was derived from previously published radio and infrared data. A least squares fit to their mass loss rates for O stars yielded the expression

$$\dot{M} = 6.8 \times 10^{-13} L^{1.10 \pm 0.06} \; M_\odot \; yr^{-1}.$$

When applied to the maximum luminosity attained by the 50 $M_\odot$ model of Lamb (1978b), this expression yields a mass loss rate of $2.2(+2.8,-1.2) \times 10^{-6}$ $M_\odot$ yr^{-1}. Using Barlow and Cohen's expression for the rate of mass loss for B and A supergiants and the 15 $M_\odot$ and 25 $M_\odot$ models of Lamb, Iben, and Howard (1976) Lamb (1978a) obtained mass loss rates of

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$1.9\ (+2.6, -1.1) \times 10^{-7}\ M_\odot\ yr^{-1}$ and $1.0\ (+1.6, -0.6) \times 10^{-6}\ M_\odot\ yr^{-1}$, respectively. Thus, the mass loss rates required for any of the three model stars (15 $M_\odot$, 25 $M_\odot$, and 50 $M_\odot$) are consistent with those observed for the relevant types of supergiants.

The loss of $\sim 9\ M_\odot$ or more of material from the outer envelope of any massive star during core-hydrogen and core-helium burning will significantly affect the star's evolution. Evolutionary calculations for stars including various amounts of mass loss have been calculated by Hartwick (1967), de Loore, De Grève, and Lamers (1977), Chiosi, Nasi, and Sreenivasan (1978), among others. These studies indicate that mass loss extends the stellar lifetime, as well as altering the internal structure of the star. The semiconvective region which occurs above the convective core during core-hydrogen burning is reduced in extent, and the convective core itself is smaller than would otherwise be the case. This implies that the total amounts of ^{14}N and ^{4}He left outside the contracting convective core during core-hydrogen burning are smaller when there is mass loss, and that the distance to which the deposits extend outward is also smaller. However, the modest mass loss rates required to explain the Cas A abundances are not expected to drastically alter either the internal structure or composition.

IV. SUMMARY

The Cas A progenitor was probably a massive star that lost at least 9 $M_\odot$ of its outer envelope during the core-hydrogen and core-helium burning phases of its evolution, that is, while it was an early-type supergiant. This mass loss uncovered nitrogen and helium rich material at the stellar surface. Later mass loss from the star (which nevertheless took place at least 10^4 years prior to the supernova explosion) supplied the material which is now in the 'quasi-stationary flocculi'. Thus two periods of mass loss are required to form a consistent evolutionary picture of the Cas A progenitor. The material lost in the first mass loss episode had a composition very close to that of 'solar' material and hence did not produce compositional anomalies in the region surrounding Cas A. However, a higher than average density in the region surrounding the remnant is consistent with X-ray observations of Cas A (see Charles, Culhane, and Fabian, 1977).

We conclude that a signature of early mass loss in the massive progenitor star of a supernova may be a high $^{14}N/^{1}H$ ratio in the remnant. Thus it would be of considerable interest to investigate this abundance ratio in as many young

supernova remnants as possible.

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DISCUSSION FOLLOWING LAMB

Kwok: You said that the N and He were ejected during the F or G phase of the star, if so why is the ejection velocity 150 km/s as we know the ejection velocity in the late stage is ~ 10 km/s? Do you then mean that the progenitor of Cas A did not go from an OB supergiant to a supernova in 10^4 yrs? If N and He were ejected during the OB supergiant phase, could you explain why the gas velocity is not $\gtrsim$ 1000 km/s?

Lamb: I said that the material enriched in nitrogen and helium was possibly ejected during the F and G supergiant phase of the star. It could also have been ejected while the star was a red supergiant. The observed velocity of the nitrogen and helium enriched material is not likely to reflect the ejection velocity from the star, as the supernova explosion itself could have imparted momentum to the circumstellar material.
It seems most likely that the Cas A progenitor became a supernova after at least an oxygen core had formed. This occurs considerably more than 10^4 years after the end of core helium burning, the epoch when the transition from OB supergiant to red supergiant is thought to take place for stars in the approximate mass range $10 \leq M_o \leq 25$. For stars more massive than 25 M_o the motion in the HR diagram is less certain at present.
It would seem very unlikely that the nitrogen and helium were ejected during the OB supergiant phase because:
a) the observed velocities are not $\gtrsim$ 1000 km/s, and
b) the material would now be outside the present supernova remnant.

de Loore: Can you comment on the fact that your 25 M_o star goes back to the blue part of the HRD at a rather blue point. Is this due to your treatment of convection and has this not as consequence a large or too extensive mixing?

Lamb: We find that the 25 M_o star does not cross the Hertzsprung gap prior to core Ne-burning. It is not obvious that this is due to our treatment of convection, and the matter requires further investigation. Consistent with the star not becoming a red supergiant no convective envelope forms, rather the convective shell present above the H-burning shell during early core He-burning in all massive stars persists throughout the evolution followed, for our 25 M_o model. The subsequent convective mixing in this model is thus not as extensive as that in the 15 M_o model, which acquires a convective envelope.

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Chiosi: Concerning the location in the HR diagram of core He-burning models of massive stars, I would like to ask if you expect that the presence of mass loss during the previous phases (core and shell H-burning) will affect this location. More specifically, your computations show that these models get bluer as the mass of the star increases (constant mass evolution). I have the feeling that the inclusion of mass loss during the core H-burning would on contrary produce redder models in core He-burning. The reason of it might be perhaps attributed to the chemical profile of these models which is such to prevent them from reaching thermal equilibrium at high effective temperature. In any case the final answer to this question is only possible taking into account the occurrence of mass loss also at low effective temperature.

Lamb: In our calculations of the evolution of massive stars of 15 $M_\odot$ and 25 $M_\odot$ (Lamb, Iben and Howard, Ap.J. 207, 209, 1976), we found that the main core He-burning phase of the evolution takes place at slightly higher surface temperatures for the more massive star (~ 0.5 in the log of the surface temperature). As shown in the above mentioned paper this agrees with Humphrey's (Ap.Letters 6, 1, 1970) observations of the distribution of blue supergiants in the HR diagram. Significant mass loss would be expected to shift the location of the core He-burning region in the HR diagram.

Sreenivasan: I believe, in your paper with Howard and Iben (Ap.J. 1977), that there were alternate convective and radiative regions outside the shrinking core of your massive star models. You said that such structure can mimic semi-convection regions. If so, I wonder why there exists a difference regarding the question of blue versus red supergiant stages. I agree, however, that one should understand the origin of these differences more clearly.

Lamb: The region of alternating convective and radiative shells outside the shrinking core is a so called semi-convective region. The criterion for convective stability used in our calculations was the Schwarzschild criterion. The ratio of times spent as a blue versus red supergiant would be different if we had used the Ledoux criterion.

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