POSSIBLE CHARACTERISTICS OF SUPERNOVA INDUCED ENRICHMENT OF GLOBULAR CLUSTERS

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Within globular clusters, stars of similar temperatures and gravities commonly exhibit differences in the strength of the $\lambda 3883$ CN band, the distribution of which is often bimodal. An archetype example of this phenomenon is NGC 6752 (Norris et al. 1981). As documented by Da Costa and Cottrell (1980), and Norris et al. (1981), the CN-rich giants in this cluster possess enhancements in nitrogen abundance by factors of 7-8 relative to the CN-poor giants. This may indicate that chemical enrichment of proto-cluster gas clouds took place as a result of the activity of massive stars, which manufactured nitrogen within their interiors and ejected it into the cluster gas while low mass stars were forming. The aim of this paper is to investigate whether the properties of NGC 6752 mentioned above might be consistent with supernova enrichment. Both the free and adiabatic expansion phases of supernova shells (Spitzer 1968) will be discussed in this context.

The Free Expansion Phase

A proto-cluster gas cloud is idealized to be spherical in shape, with an internal density distribution of the form $\rho(r) = \rho_o\, r^{-2}$, where r is the distance from the cloud center. Upon denoting the total cloud mass as M_6 (in units of $10^6\ M_\odot$), and the cloud radius as R, the density distribution can be written as

$$\rho(r) = 5.42\times10^{-24}\ M_6\ R_{100}^{-1}\ r_{100}^{-2} \quad \mathrm{gm\ cm^{-3}},$$

where a subscript of 100 denotes that a length is being expressed in units of 100 parsecs.

Suppose that a supernova explosion occurs at a distance of $r_{1,100}$ from the cloud center. Initially the ejecta will expand at constant velocity, until the mass of ambient material that has been swept up exceeds the mass of the stellar ejecta. The radius $s_{a,100}$ of the bubble at this time will be

$$s_{a,100} = 1.44\times10^{-2}\ (M_j/M_6)\ R_{100}^{1/3}\ r_{1,100}^{2/3},$$

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where M_j is the mass (in units of $M_\odot$) of ambient material that has been swept up. The bubble will be contained within the cloud during this phase if the site of the explosion is within a distance

$$r_{A,100} \sim 579 \, (M_6/M_j)^{1/2} \, R_{100}$$

of the cluster center. Taking M_j to be $\sim$ 10 times the mass of the stellar ejecta, which may in turn range from 1 to 10 $M_\odot$, the above relation indicates that for protoclouds of masses $M_6 > 10^{-3}$, $r_{A,100} > R_{100}$, and the supernova remnants will be contained at the conclusion of their free expansion phase.

The Adiabatic Expansion Phase

Once M_j has become sufficiently large, the supernova bubble will enter a phase of adiabatic expansion. The remnant will now become elongated, but for the purposes of the present calculations is nonetheless assumed to be spherical throughout the entire adiabatic phase. In addition, it is assumed to be small in size relative to $r_{1,100}$, so that the evolution can be treated as that of a remnant expanding into a uniform medium of density equal to that locally at $r_{1,100}$.

Throughout the adiabatic phase the total energy of the gas remains equal to the initial explosion energy E. The front of the remnant is a shock wave whose expansion for a gas of $\gamma = 5/3$ is governed by the equation $P = 2\lambda E/3V$, where P is the pressure immediately behind the shock wave, V is the volume enclosed within the remnant, and λ is defined as the ratio of the energy density behind the shock front to the average energy density within the remnant ($\sim$ 1.6; Spitzer 1968). In the strong shock approximation, the ratio of post-shock density to ambient gas density is 4. The post-shock temperature can then be calculated from the ambient density, the perfect gas relation, and the pressure. Following Spitzer (1968), it is assumed that radiative energy losses from the shock front become important when the post-shock temperature drops below 10^6 K. The radius $s_{b,100}$ of the remnant at this time is

$$s_{b,100} = \{3.04\times10^{-4} \, E_{50} \, M_6^{-1} \, R_{100} \, r_{1,100}^{2}\}^{1/3},$$

where E_{50} is the explosion energy in units of 10^{50} ergs.

The amount of ambient material that has been swept up by the remnant when it reaches this size is

$$M_B = 101 \, E_{50} \, (M_\odot).$$

The mass M_B depends only on the supernova energy, and for an explosion of $E_{50} = 10$, $\sim 10^3$ $M_\odot$ of ambient material will be swept up prior to the cessation of adiabaticity. Should the nitrogen produced by the precursor star become incorporated into this shell material, and if enriched stars can form from it, then such stars will possess abundance enhancements that reflect only the amount of nucleosynthesised material ejected by the supernova. Should stars of only a small mass range constitute the supernova precursors, the chemical enrichment induced by each would be similar, and a bimodal abundance distribution could be established within a cluster. The calculations of Renzini and Voli (1981) indicate that $\sim 0.1\ M_\odot$ of primary nitrogen could typically be ejected by intermediate mass (5-8 $M_\odot$) stars. Consider for example, a protocloud with an initial abundance of [A/H] = -1.5, [N/A] = 0. The mass of ambient nitrogen swept up would be 0.03 $M_\odot$. Upon distributing the ejected nitrogen throughout the $10^3\ M_\odot$ shell, enriched stars could be formed with a nitrogen enhancement of Δ[N/A] = $[N/A]_{new} - [N/A]_{old} = 0.64$ relative to the CN-poor stars. Such a nitrogen difference is similar to that observed between the CN-rich and CN-poor giants in NGC 6752 (Da Costa and Cottrell 1980, Norris et al. 1981). Smith and Norris (1982) estimate that the excess mass of nitrogen present in the NGC 6752 CN-rich stars, relative to that in the CN-poor, is 10 $M_\odot$. To produce this amount, 100 supernova precursors are required. The combined explosions of these stars would sweep up $10^5\ M_\odot$ of gas by the end of adiabaticity, which is consistent with the total mass of the CN-rich population within NGC 6752.

It appears that supernova enrichment, providing that it occurs near the end of the adiabatic expansion phase, can explain some of the properties of the CN-rich stars in clusters such as NGC 6752. However no physical explanation can be given as to why enriched stars should form out of the remnant material just when its expansion ceases to be adiabatic. In addition, there are other observations and constraints which a supernova enrichment scenario must be able to accommodate, and two of the most important of these are as follows.

(i) In view of the apparently large number of intermediate mass stars needed in clusters such as NGC 6752, confinement of the supernova ejecta within the protocloud poses a serious problem. It may be that the stars which produce primary nitrogen do not explode as supernovae, but instead distribute their products by means of a stellar wind (e.g. Kennicutt [1984] finds a lower mass limit to Type II supernova precursors of 8 $M_\odot$).

(ii) The CN-rich giants in NGC 6752 are depleted in carbon by a factor of Δ[C/A] $\sim$ 0.3 relative to the CN-poor giants (Da Costa and Cottrell 1980, Norris et al. 1981). This phenomenon is common to other clusters such as M3 and M13 (Suntzeff 1981), and as discussed by Smith and Norris (1982), is difficult to account for in terms of a primordial enrichment framework. It suggests instead that the CN anomalies originate within the CN hydrogen burning regions of the cluster giants themselves. A recent discussion of this possibility is given by Langer and Kraft (1984).

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