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The nature of the progenitors of supernovae of type I

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Abstract. This paper examines the hypothesis that supernovae of type I are produced by relatively 'young' single stars. The fact that SN I are not concentrated in spiral arms implies that their progenitors have $M \lesssim 8 M_\odot$. The existence of white dwarfs in open clusters places a limit $M \gtrsim 5 M_\odot$ on SN I progenitors.

The similarity of the colours of ellipticals that have produced supernovae to that of E galaxies which have not implies that young stellar populations cannot contribute more than 3 per cent of the ultraviolet light of supernova-prone ellipticals. It follows that the hypothetical young stellar population in supernova-prone ellipticals must produce SN I 17 times as efficiently (per unit of ultraviolet luminosity) as do Sc galaxies. This would only be possible if the mass spectrum of star formation in ellipticals is very sharply peaked at $M \simeq 5 M_\odot$. It is also shown (see figure 1) that hydrogen-rich E galaxies are, in the mean, less luminous than those which are not observed to contain hydrogen.

Observations of the Virgo cluster show no significant difference between the velocity dispersion of E galaxies that have produced supernovae and those which have not. Such a difference might have been expected on the hypothesis that SN I are associated with a relatively young stellar population. This is so because high-velocity ellipticals are most likely to have had their star producing hydrogen gas removed by ram pressure stripping.

Finally it is pointed out that galactic SN I have a rather large $|z|$, which is contrary to expectation for objects with massive progenitors.

On balance the available evidence does not appear to favour the idea that SN I are produced by single relatively-young progenitors.

Key word : supernovae

1. Introduction

Recently a number of authors (Oemler & Tinsley 1979, Caldwell & Oemler 1981) have argued that supernovae of type I (SN I) are produced by intermediate-mass stars.

The fact that SN I are *not* concentrated in spiral arms (Maza & van den Bergh 1976) shows that the progenitors of these objects must be older than 3×10^7 yr and hence have masses (Becker 1981) $\lesssim 8\ M_\odot$. On the other hand Anthony-Twarog (1982) has used observations of open clusters to show that stars with ages $\gtrsim 6\times10^7$ yr and masses M $\lesssim 5\ M_\odot$ evolve into normal white dwarfs. If SN I are produced by single stars they must therefore have formed in a relatively narrow window $3\times10^7 \lesssim$ age $\lesssim 6\times10^7$ yr and $5 \lesssim M/M_\odot \lesssim 8$. Evidence for such relatively recent star formation should be observable in E and S0 galaxies that have recently produced supernovae.

2. Colours of elliptical galaxies

If star formation has taken place in supernova producing E galaxies within the last $\sim 5\times10^7$ yr then such objects might be expected to be significantly bluer than ellipticals in which no SN I have been seen. This is not observed to be the case. Sandage & Visvanathan (1978) have published colours for 8 galaxies of types E and E/S0 (Sandage & Tammann 1981) which have produced supernovae (Kowal 1981). The mean colour of these objects is $\langle u-V\rangle^{\rm KEM}_{0.5}=2.37\pm0.02$ m.e. This may be compared to $\langle u-V\rangle^{\rm KEM}_{0.5}=2.33\pm0.01$ for all E and S0 galaxies studied by Sandage and Visvanathan. This result shows that supernova producing ellipticals are *not* bluer than those in which no supernovae have been observed, *i.e.* the $(u-V)$ colours give no support to the hypothesis that supernovae in E galaxies are associated with a young stellar population. Alternatively one might make the *ad hoc* assumption that the blue colour of young stars in supernova-prone ellipticals is exactly compensated for by the reddening produced by intersteller dust embedded in the star forming gas. At present there is no evidence that E galaxies which have produced supernovae are particularly dusty. It might, however, be worthwhile to check this conclusion on homogeneous plate material.

From the colour observations quoted above an average colour as blue as $\langle u-V\rangle = 2.30$ for SN I producing E + E/S0 galaxies can be excluded at the $3\,\sigma$ level. Ignoring the possible effects of internal reddening it then follows that not more than ~ 3 per cent of the ultraviolet ($\lambda\sim 3550$ Å) light in supernova-prone ellipticals can be produced by young stars.

According to Oemler & Tinsley (1979) Sc galaxies produce ~ 4 times as many SN I per unit blue luminosity as do ellipticals. Per unit ultraviolet luminosity Sc galaxies are therefore ~ 2 times as prolific as ellipticals. *If* all the supernovae in ellipticals are produced by their young population component (which contributes $\lesssim 3$ per cent of their ultraviolet light) then this hypothetical young population in ellipticals must be producing SN I *at least* 17 times as efficiently as the stellar population in spirals of type Sc! Clearly this would only be possible if the present mass-spectrum of star formation in E galaxies peaks sharply in the $5\,M_\odot$ to $8\ M_\odot$ range. Furthermore the fact that no SN II have ever been observed in ellipticals shows that the mass spectrum of star formation (if it occurs at all in normal ellipticals) can not extend to very large masses. The absence of H II regions in normal ellipticals implies absence of stars with $M > 15\ M_\odot$. From the local luminosity function and the observed rate of SN II Tammann (1981) finds $M\,(\text{SN II}) > 8.4\ M_\odot$. If this value is correct the mass spectrum of star formation in E galaxies must be very sharply guillotined at 8 $M_\odot$ to form SN I with $5 < M < 8\ M_\odot$ without also forming some SN II with $M/M_\odot > 8.4$.

A problem with the hypothesis that SN I are only produced by stars with $5 < M/M_\odot < 8$ is that such objects should exhibit Population I kinematics. However, observations of the three (1006, 1572, 1604) historical SN I yields (Tammann 1982) $\langle |z| \rangle = 316$ pc; a value which is characteristic of an old disk population rather than of extreme population I. The fact that the Lupus supernova of 1006, which was the nearest supernova observed in historical times, had $z = 0.4$ kpc suggests that the rather large value of $\langle |z| \rangle$ found above is not entirely due to selection effects which discriminate against highly reddened low-latitude objects.

3. Elliptical galaxies containing gas

Star formation requires the presence of significant amounts of gas. Ellipticals in which H I has been detected might therefore be more supernova-prone than those in which no gas has been observed. Recently Gouguenheim (1979) has listed 11 ellipticals in which H I has been detected. In the subsequent discussion we shall (i) delete NGC 3773 = MRK 743, which is a peculiar object with a jet, from Gouguenheim's sample and (ii) consider only those galaxies classified E or E/S0 by Sandage & Tammann (1981) which have $B^0_T < 12.6$. The latter restriction is imposed because faint Shapley-Ames galaxies are less closely monitored for supernovae than are brighter ones. In the total sample of 120 E or E/S0 galaxies 9 supernovae have been observed (Kowal 1981) yielding N(SN)/N (Gal) = 0.08 ± 0.03 m.e. In the 6 E or E/S0 galaxies in which H I has been detected 2 supernovae (1971c in NGC 3904 and 1939a in NGC 4636) have been discovered yielding N(SN)/N(Gal) = 0.33 ± 0.27. These very small number statistics are not inconsistent with the notion that gas-rich ellipticals might be more supernova-prone than gas-poor ones.

It is of some interest to note (see figure 1) that the E + E/S0 galaxies that contain H I are, in the mean, significantly fainter than those in which no gas has been detected. Possibly stellar winds (Mathews & Baker 1971), which sweep gas out of galaxies, are most intense in luminous objects. If gas-rich ellipticals form stars, and hence eventually SN I, then faint E galaxies should be more prolific supernova producers (per unit luminosity) than bright ones. The data plotted in figure 1 show, albeit at a low level of statistical significance, no evidence for such an effect.

Sandage & Visvanathan (1978) give $u-V$ colours, corrected for foreground reddening and reduced to $M_V = -21.7$, for 7 of the E and E/S0 galaxies listed by Gouguenheim (1979). For these objects $\langle u - V \rangle^{\mathrm{KEM}}_{0.5} = 2.33 \pm 0.08$, which is identical to $\langle u - V \rangle^{\mathrm{KEM}}_{0.5} = 2.33 \pm 0.01$ which Sandage & Visvanathan find for all E and S0 galaxies. It follows that there is no evidence for the presence of significant numbers of young blue stars in the sample of elliptical galaxies in which H I has been observed.

4. Do SN I occur in S0 galaxies?

Oemler & Tinsley (1979) comment on the paucity of supernovae in S0 galaxies. Since the S0 classification type is difficult to recognize on Schmidt plates it seems

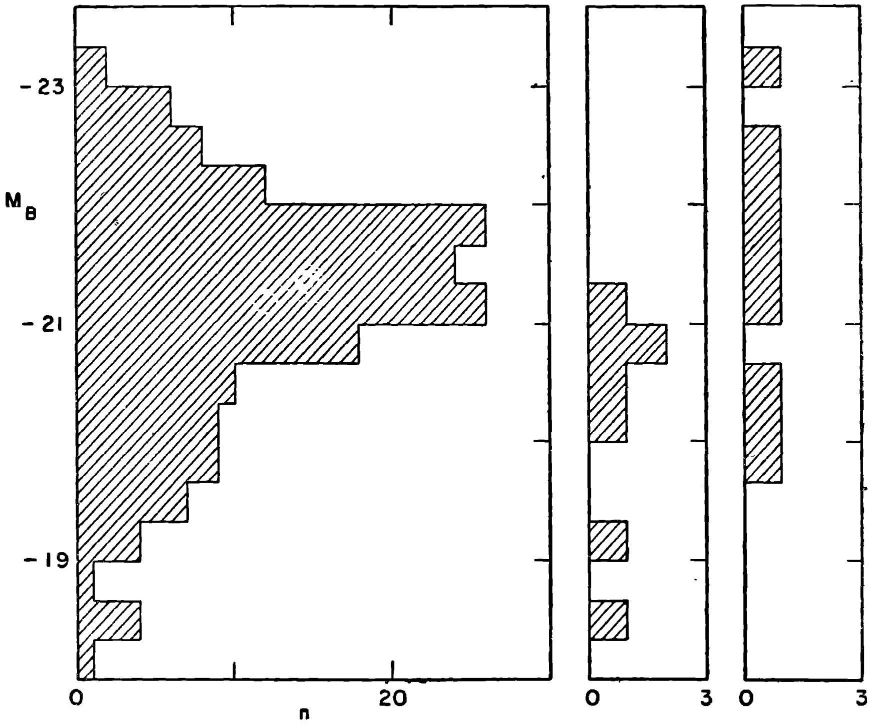

Figure 1. Left panel : Absolute magnitude distribution of all E and E/S0 galaxies with $B_T^0 < 12.6$.

Centre panel : Absolute magnitude distribution of seven E galaxies with $B_T^0 < 12.6$ which, according to Gouguenheim contain H I. The figure shows that E galaxies containing H I are systematically fainter than typical ellipticals. Right panel : Absolute magnitudes of all E + E/S0 galaxies with $B_T^0 < 12.6$ in which supernovae have been discovered.

best to rely only on the homogeneous classifications given by Sandage & Tammann (1981). Their *Revised Shapley-Ames Catalog* contains 151 E galaxies, which produced 9 supernovae, and 154 S0 + SB0 galaxies in which 8 supernovae have been discovered (Kowal 1981). According to van den Bergh & McClure (1979) the average luminosity of E galaxies in the *Revised Shapley-Ames Catalog* is significantly greater than that of S0s. It follows that the supernova rate per unit luminosity is actually larger (at a statistically marginal level of significance) in lenticulars than it is in ellipticals. The high SN I rate in lenticular galaxies appears to be due mainly to the large fraction of S0pec and SB0pec galaxies in which supernovae have been detected. The number of supernovae observed in 18 peculiar S0 + SB0 galaxies equals that seen in 232 normal lenticulars. Possibly the high supernova rate in objects such as NGC 5195 (SB0pec) is related to the high SN I frequency observed in NGC 5253, which has been discussed by van den Bergh (1980). In that paper it was suggested that both the morphological peculiarities and the high rate of SN I occurrence in this galaxy result from a burst of star formation that took place a few times 10^8 yr ago. In a possibly related observation Thompson (1981) points out that only 8 (0.4 per cent) of all Coma cluster galaxies are of type I0, yet these 8 objects have produced 2 of the 7 (29 per cent) of the supernovae that have so far been discovered in this cluster. Some (but not all) I0 galaxies were classified 'amorphous' by Sandage & Tammann (1981).

5. Do gas-poor E + S0 galaxies produce fewer SN I ?

In a recent paper Caldwell & Oemler (1981) suggest that the supernova rate in E + S0 galaxies is lower in the "swept" (*cf.* Gunn & Gott 1972) core regions of clusters than it is for E + S0 galaxies in the outer parts of clusters. Since this result is based on observations of only 12 supernovae in clusters it is critically important that the classifications of all parent galaxies of these supernovae be correct. In the subsequent discussion it will be assumed that only those 7 galaxies that were independently classified E or S0 by *both* Caldwell & Oemler (1981) and by Maza & van den Bergh (1976) have reliable classifications. The supernova rates derived for these seven objects are listed in table 1. The data in this table show no significant difference between the supernova frequency of E + S0 galaxies in different cluster regions.

Table 1. Observed supernova rates

Region	Galaxy-months*	Supernovae	Rate/Galaxy-month
I (Swept cluster core)	8270	2	$(2.4 \pm 1.7) \times 10^{-4}$
II (Intermediate zone)	10594	1	$(0.9 \pm 0.9) \times 10^{-4}$
III (Cluster envelope)	22037	4	$(1.8 \pm 0.9) \times 10^{-4}$

*The number of galaxy-months during which each region had been surveyed was taken from Caldwell & Oemler (1981).

As a result of ram pressure stripping (Gunn & Gott 1972) Virgo cluster E + E/S0 galaxies that contain gas might be expected to exhibit a lower velocity dispersion than those that are gas-free. If relatively recent star formation results in the occurrence of SN I one might expect supernovae to avoid galaxies with radial velocities that differ greatly from that of the cluster mean. This is not observed to be the case. For an almost complete sample of 61 E + S0 galaxies with $B_T < 14.0$ within 6°.0 of M 87 (Kraan-Korteweg 1982) $\langle V_0 \rangle = 977 \pm 69$ km s^{-1} with a dispersion of $\sigma = 540$ km s^{-1}. The latter value does not differ significantly from $\sigma = 473$ km s^{-1} that is obtained for the 7 Virgo E + S0 galaxies in which supernovae have been observed (Kowal 1981).

6. Conclusions

What kinds of objects could be the progenitors of SN I if they are not single stars with $M \sim 7\, M_\odot$? The fact that only ~ 1 per cent of all stars currently evolving in E galaxies become supernovae indicates that supernova progenitors must fulfill quite special conditions. Perhaps the most plausible suggestion that has so far been made (Schatzman 1963; van den Heuvel 1981; Nomoto 1982a, b; Fujimoto & Sumimoto 1982) is that SN I result from the accretion-induced detonation of white dwarfs in close binary systems. Such models allow the precursors of SN I to have any age $\gtrsim 1 \times 10^8$ yr. Galaxies which have formed stars actively during the last few billion year will, on such a model, have a higher supernova rate than elliptical galaxies in which all stars are very old (Greggio & Renzini 1982). This accounts for the observation (Tammann 1974) that the present rate of supernovae of type I, per unit luminosity, is greater in Sc galaxies than it is in ellipticals. An extreme example of this effect is seen in NGC 5253 (van den Bergh 1980) which appears to have experienced a violent burst of star formation between 1×10^8 and 1×10^9 yr ago.

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