ON THE CORRELATION BETWEEN SUPERNOVA OCCURRENCE AND NUCLEAR ACTIVITY IN ELLIPTICAL GALAXIES

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Abstract. We show that there is a correlation between the occurrence of supernovae and nuclear activity in elliptical galaxies. Both shun a canonical elliptical and occur only in those ellipticals which accrete gas. We also show that the hypothesis that all SNI come from short-lived stars is consistent with the colour observations of elliptical galaxies. We propose that there is a class of intrisically rounder, massive, dusty, metal-rich ellipticals which produce supernovae and are more likely to contain a radio source.

1. Introduction

We show that there is a correlation between the occurrence of supernovae (SN) and nuclear activity in elliptical (E) galaxies. In Section 2, we argue that the progenitors of SNI are short-lived stars (Oemler and Tinsley, 1979). It is our contention that a typical E galaxy which is gas-free and contains only low-mass stars does not produce SN. Only if an E is so placed that it accretes matter and forms stars will it produce SN. Indeed we introduce in this paper the concept of a supernovic E: an E galaxy which can produce SN is termed a supernov E. Of course, some supernovic galaxies will be more supernova, prone than others. A supernovic E may accrete gas from its own halo (e.g. N4406 = M86) or from the intergalactic or intracluster medium (N1275 = Per A, N 4486 = M87) or from a neighbouring galaxy (N 3226). Alternatively or simultaneously an E may swallow gas clouds or preferably gas-rich dwarf galaxies (N 1316 = For A).

Radio observations of E galaxies are interpreted in terms of a central engine (e.g. a black hole) which uses gas as fuel and transforms energy from a passive form into an active form. Now since a typical E galaxy is gas-free, a central engine in such a galaxy – even if it existed – would lie idle for want of fuel. However, if an elliptical accretes gas from outside, in course of time this gas would find its way to the nuclear regions and give rise to nuclear activity (Shklovskii, 1963). Thus star formation, occurrence of SN and nuclear activity in elliptical galaxies are interrelated and a consequence of accretion of gas by the galaxy.

We discuss in Section 4 why a supernovic E does not appear as blue as it should if it recently formed stars. We proceed to identify a class of massive, intrinsically rounder, dusty, metal-rich ellipticals with higher velocity dispersions which undergo recurrent bursts of star formation with a steep initial mass function (IMF) truncated at $\sim 7\ M_{\odot}$. We suggest that detailed multicolour surface photometry should be undertaken of supernovic and potentially supernovic E galaxies to

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identify the isolated star-forming regions. A finding list of such galaxies will be given elsewhere.

Though the elliptical and the lenticular (L) galaxies have similar photometric properties (Sandage and Visvanathan, 1978a, b), the L galaxies do not form extended radio sources. It appears that the strong radio galaxies classified L are actually misclassified E or D galaxies (cf. Balick and Heckman, 1982). Therefore, while we restrict the discussion of radio properties of E galaxies, we include L galaxies in the discussion of colours.

2. Progenitors of SNI

The occurrence of SNI in E galaxies – which presumably consist of only old stars – has been interpreted to mean that SNI progenitors are low-mass stars. A popular model in this context has been the one due to Whelan and Iben (1973) in which a white dwarf in a close binary accretes matter from its companion and crosses the Chandrasekhar limit. In recent times this picture has come under severe strain. The number of SNI per unit galaxy luminosity increases along the Hubble sequence, E–L–Sa–SB–Sc–Im, along which the young stellar content also increases. If SNI came from old, low-mass stars, the trend would have been just the opposite. The proportionality of SNI rates in spiral galaxies to their star formation rates demands that SNI progenitors have masses $\gtrsim 2\ M_\odot$.

The SNI rate is the highest in I0 galaxies – which are morphologically not all alike but show signs of intense star formation; this immediately suggests that SNI are related to recent star formation. If one postulates that all SNI have similar progenitors – and the extreme homogeneity of SNI supports this – then one is led to the conclusion that all SN, including those in E galaxies, come from short-lived stars (4–7 $M_\odot$; cf. Oemler and Tinsley, 1979).

The theoretical models of the spectra and the light curve of SNI place constraints on the possible progenitor candidates. The absence of hydrogen in the SNI spectra demands that the progenitors be hydrogen poor. The exploding star should have a helium-rich envelope around it (so that peak luminosity and the early spectra can be explained) and the explosion itself should eject $\sim 0.5\ M_\odot$ of nickel (to explain the late-time light curve and spectra). The helium envelope should have a constant velocity of 11 000 km s^{-1} during peak luminosity, and the velocity should decrease at later times to $\sim$ 8000 km s^{-1}. It does not seem possible to obtain 0.5 $M_\odot$ of nickel without totally disrupting the star; thus models which leave behind a compact star are ruled out (Wheeler *et al.*, 1980).

Although no single model can explain all the features satisfactorily, the most plausible models for SNI are the carbon deflagration models (Nomoto, 1981) which require intermediate mass stars as progenitors. In one successful model, a carbon-oxygen (C–O) white dwarf undergoes slow helium accretion from a companion in a close binary and is totally disrupted by carbon deflagration. Such a white dwarf corresponds to an electron-degenerate C – O core of a star less massive than 8 $M_\odot$. It should be noted that if the accretion onto the white dwarf is not slow, but rapid, a red giant envelope would form over hydrogen- and helium-burning shells and the explosion, if at all it occurs, will not be SNI (Wheeler *et al.*, 1980). The specific model of Whelan and Iben (1973) involves rapid mass transfer and is thus unlikely to correspond to a SNI. If a single star $(6 \pm 2) < M/M_\odot < (8 \pm 2)$ can somehow lose its hydrogen envelope, the resulting 1.5–2 $M_\odot$ helium star with a degenerate C–O core will also evolve to explode as a carbon-deflagration supernova. The frequency of SNI in various galaxy types is consistent with the white dwarf model where the primary starts with a main sequence mass ~ 8 $M_\odot$ (Greggio and Renzini, 1983).

The fact that E galaxies have produced only SNI means that stars more massive than 7 $M_\odot$ do not form in them. We would like to suggest that, as one moves along the Hubble sequence, the initial mass-function (IMF) becomes shallower. The observed correlation between mass-to-luminosity ratio and $(B-V)$ colours of spiral galaxies tends to support this hypothesis (Sargent and Tinsley, 1974). If very many massive stars form, the energetics associated with them will heat and disperse the interstellar gas, with the result that the next phase of star formation would be delayed (Seiden and Gerola, 1982). By the time the next phase of star formation takes place, the earlier stars would have completed their evolution, returning most of the gas back to the interstellar medium. Thus a shallow IMF will ensure a perennial availability of gas. On the other hand, if IMF is steep, a larger fraction of the gas available would be used up in star formation.

3. Galactic Ecology

If an elliptical accretes matter, it may show up as neutral hydrogen and/or dust. It is this matter we hold responsible for SN as well as nuclear activity.

Hummel (1980) has convincingly shown that elliptical galaxies with detected H I are much more likely to contain nuclear emission-line regions and nuclear continuum radio emission than ellipticals without detected H I, suggesting that the accreted gas fuels the central source. Confirmed H I detections are available for only two NGC ellipticals, N 1052 and N 4278. In 16 others, H I has been detected and eight earlier detections have not been confirmed (Knapp, 1982). Shostak *et al.* (1983) show that the H I detection rate in radio galaxies is consistent with the presence of thin H I disks of galactic dimensions in all radio galaxies. Sparks (1983) argues that the colours of radio ellipticals imply a dust extinction of ~ 0.18 mag in the V band. He also finds that this conclusion is consistent with the H I and emission line observations. In the case of 8 radio ellipticals with dust lanes, radio axis is perpendicular to the dust lane (Kotanyi and Ekers, 1979), again highlighting the connection between accretion and radioactivity.

The connection between radio activity and occurrence of SN is brought out by the Arecibo 2380 MHz Survey (Dressel and Condon, 1978) of bright galaxies which includes 10 supernovic E galaxies. Six of these 10 have been detected above the 3σ limit. These numbers may be compared with a total of 52 galaxies detected out of 204 observed Es. Thus, the radio detection rate is 2.3 times higher in the supernovic sample. In order to eliminate the distance-dependent bias, Dressel (1981) has defined a parameter

$$R = S\,\mathrm{dex}\left(\frac{m - 12.5}{2.5}\right),$$

where S is the 2380 MHz flux density in mJy and m the apparent photographic magnitude. Three out of ten supernovic Es have $R > 50$, while the corresponding fraction is only 15% for the total sample. We are again led to the conclusion that radio activity occurs twice more often in supernovic Es, than in the general sample. Hummel *et al.* (1983) have compiled a list of 123 Es from optically selected samples observed at 1400 MHz. Twenty-four of these have been detected at this radio frequency. The list includes 9 supernovic Es of which 3 are radio detected. This indicates a radio detection probability for supernovic Es 1.7 times that for the general sample. This value increases to 2.8 if we include the two galaxies (N 3226, N 7619) detected at 2380 MHz but not at 1400 MHz. Furthermore, Hummel, Kotanyi and Ekers define a complete 'local sample' in which the radio detection probability is 33%. Among four supernovic Es in this subset, only one (N 4621) has not been detected at 7 mJy level. Similarly in Heckman's (1983) Sample 2 – which is based on the criterion of radio detection and not power – there are six supernovic galaxies out of 44 radio-detected ellipticals, as against 3 out of 60 not detected. Thus we conclude that radio activity is found at least twice as often among supernovic Es as in the general sample. Table I lists all the Es from de Vaucouleurs *et al.* (1976; hereafter RC2), that have produced supernovae. The galaxy N 1316 classified as L and N 1275 classified as pec are also included in the list since they are now known to be ellipsoidal (see Section 1). Out of these 22 galaxies, 14 have been looked at in the radio region and only 4 of these 14 are not detected.

The suggestion that it is gas accreted by an elliptical galaxy that fuels the nuclear activity finds support from observations of radio spirals. Nuclear sources in barred spirals are on an average brighter than those in non-barred spirals, and nuclear sources in double galaxies are brighter than in isolated galaxies (Hummel, 1980). Whereas in the case of paired galaxies the supply of gas to the central regions is ensured by tidal interaction, the centres of barred spirals receive their fuel supplies as a result of the interaction of the bar with the gas in the disk.

The environments of an E galaxy play the same role as the disk of a barred spiral, that is, they ensure the central regions of fuel supply. Thus an elliptical galaxy is more likely to be a radio source if it is in a Zwicky cluster, and is still more likely to be a radio source if it is in a group within a cluster (Dressel, 1981). 59% of the supernovic NGC ellipticals (10 out of 17) have been detected at radio wavelengths, (among the remaining galaxies, three have not been looked at in the radio). Furthermore, 33% of the supernovic ellipticals show [O II] $\lambda3727$

TABLE I

Bright supernovic ellipticals

NGC	UGC	Radio designation	RMT	S_{2380} mJy	R	SN
1275	2669	3C84	P	11 700	18 500	1968a
1316		PKS0320–37	PLXS0pec	89 300	6600	1980n, 1981d
2672	4619		E1+	< 12	< 27	1938b
3226	5617		E2: pec	12	27	1976k
3834			E			1968f
3904			E2+:			1971c
4335			E2			1955e
4374	7494	3C272.1	E1	3 635	759	1955e
4486	7654	3C274	E+0+pec	134 200	19 398	1919a
4564	7773		E6	< 12	< 12	1961h
4621	7858		E5	< 12	< 3	1939b
4636	7878		E0+	64	34	1939a
4782		3C278	E0pec	4500	5700	1956b
4874	8103	PKS 1257+28	E+0	132	399	1968b, 1981g
5090		PKS 1318−434	E2	4900	4500	1981c
7619	12523		E2	22	26	1970j
7768	12806		E2	< 12	< 48	1968z

Note: N3834 is not classified in RC2. Other RC2 E galaxies with SN are I4051 (1950a), I5342 (1961n), A1248+28 (1961d), A1255+28 (1963m), A2338+26 (UGC 12733; 1969k) none of which are looked at in the radio region.

emission, whereas only 15 % of all ellipticals show this emission (Osterbrock, 1960). Out of the 17 supernovic ellipticals, six have yet shown no evidence of dust, gas or radio emission. The correction between SN occurrence and the other manifestations of the presence of gas is sufficiently strong to warrant a close scrutiny of these apparent exceptions.

The Virgo cluster brings out the salient features of galactic ecology, convincingly showing how the environments influence the properties of the ellipticals. Most of the ellipticals in the region $12^h < \alpha < 13^h$, $0° < \delta < 20°$ are probably members of the cluster. Whereas this region contains only 11 % of the NGC ELs, it accounts for 30 % of the supernovic NGC ELs. This shows that the Virgo ELs are nearly thrice as prolific SN-producers as the general sample of ELs. This figure of 30 % does not include the unconfirmed SN 1969 in the elliptical N 4372 nor SN 1965 in the elliptical-spiral interacting pair N4410 A, B. Also excluded is the intergalactic SN 1980i between the ellipticals N 4374 (M84) and N 4406 (M86). The Virgo cluster is a very well-studied object. However, the SN yield of galaxies does not seem to depend on the search intensity of the fields in which they are located (Tammann, 1974).

The Virgo cluster shows a two-component X-ray spectrum; the cluster is permeated by a hot ($\sim 10^8$ K) intracluster gas in which are embedded galaxies with individual cool ($\sim 10^7$ K) atmospheres (Forman *et al.*, 1981). The non-thermal activity in the central regions of N 4486 (M87) is explained in terms of accretion from its massive halo (Mathews, 1978). We hold this accretion responsible for the SN also. A similar case is that of the powerful X-ray and radio source N 1275 (Per A) (Fabian and Nulsen, 1977), which has also produced a SN. X-ray haloes have been detected around M84 and M86 (Forman *et al.*, 1981). It is reasonable to suppose that other ellipticals in the Virgo cluster too would have similar haloes, confined by the hot intracluster gas (Fabian *et al.*, 1980). The presence of individual gas reservoirs around ellipticals from which they can accrete gas explains why Virgo ellipticals are predominantly supernovic and radio active.

The hot gas (10^8 K) in the compact, dynamically evolved, spiral-poor Coma cluster is associated with the cluster as a whole and not with any individual galaxy. It approximates an isothermal gas sphere and shows no sign of radiatively regulated accretion (Forman *et al.*, 1981). There are indications that SN rate in Coma is about a factor of 3 lower than in Virgo (Barbon, 1978). Coma cluster is fairly uniform in galaxy type and shows a central maximum density and a symmetrical decrease towards the boundaries. If all galaxies were equally likely to produce SN, we should expect the supernovic ellipticals to have the same distribution as the galaxies in general. This, however, is not the case. All supernovic ELs in Coma are confined to a plane (Barbon, 1978). Presumably, some gas in Coma has settled down in a disk and is accreted by the galaxies there, giving rise to supernovic activity. Of the 7 SN in the central regions of Coma, 2 have occurred in I0 galaxies, 4 in EL galaxies and only 1 in a Sb galaxy (Thomson, 1981). At the centre of the cluster and the disk lies the giant elliptical radio galaxy N 4874 which has produced 2 SN.

Further support for the accretion hypothesis comes from Caldwell and Oemler (1981), who find that the spiral-rich outer regions of rich clusters of galaxies have higher SN rate in the EL galaxies as compared to the spiral-poor and gas-poor central regions of such clusters. They also find that the EL galaxies in the outer regions of rich clusters are bluer than the ones in the inner regions suggesting that recent star formation is more active in the EL galaxies embedded in gas-rich outer regions of the rich clusters.

4. Colours of Supernovic Ellipticals

If SNI come from short-lived stars, the E galaxies that produce SN should be bluer than the ones which do not. Oemler and Tinsley (1979), using a monotonically decreasing star formation rate (SFR), estimated the ELs should appear bluer by 0.04 mag in $B-V$ and 0.12 mag in $U-B$ if they were all to form stars at a rate dictated by SN statistics. If the IMF is truncated at 6.5 $M_\odot$, the corresponding numbers would be 0.05 and 0.09 mag. These values are higher than the amount of intrinsic scatter in the observed colours and would increase further if only a peculiar fraction of ELs produce SN.

However, there is no obvious reason why the ELs should have been forming stars for the past 10^{10} yr as Oemler and Tinsley have assumed. The accretion and consequent star formation may only be a current or recurrent phase in the lives of EL galaxies. Tammann (1978) derives an SN rate of $0.16\ \mathrm{SN} \times 10^{-10}\ L_{\odot}^{-1} \times 10^{-2}$ yr^{-1} if observed SN were distributed among all ELs. This rate implies an SFR of $0.088\ M_{\odot}\ \mathrm{yr}^{-1}$ in terms of a standard IMF truncated at $7\ M_{\odot}$. If star formation continues at this rate in an EL galaxy with $V = 21.0$ and $U-V = 1.47$, then using the models of Struck-Marcell and Tinsley (1978), we find that the Galaxy would be bluer by only 0.03 mag in $U-V$ at the end of 10^8 yr. If SN occur only in one-third of all ELs we would obtain a blue excess of 0.09 in $U-V$ for supernovic ELs. Furthermore, the galaxies in which the star formation does not continue for 10^8 yr and the galaxies which have ceased to form stars would lie between this blue limit and the locus of normal ELs.

Sandage and Visvanathan (1978a, b) give corrected photoelectric colours for a sample of 354 unambiguous E and L galaxies out of which 12 Es and 8 Ls have produced SN. Excluding the very blue lenticular N 4382 $[(U-V)_{0.5}^{\mathrm{KEM}} = 2.08]$, one obtains a mean value of $\langle (U-V)_{0.5}^{\mathrm{KEM}} \rangle = 2.35 \pm 0.05$ for supernovic ELs – not significantly different from the value 2.33 ± 0.09 for the whole sample. We discuss in the following some of the mechanisms which make the colours of supernovic, radio ellipticals conform with the general sample.

Sparks (1983) has shown that the radio ellipticals are redder than the normal ones. Using the two-colour diagrams to separate the radio-loud and radio-quiet ellipticals, he argues that the radio ellipticals are reddened by dust. In particular, the Virgo supernovic ellipticals N 4374 and N 4636 appear to suffer an extinction of $A \sim 0.20$ mag due to dust. If we assume that $E(U-V) = 0.63\ A_v$, the implied reddening due to dust is comparable in magnitude to the blue excess expected from recent star formation.

The C–M relation for the ELs is understood to be a result of the metallicity – absolute magnitude relation (Visvanathan, 1979). The high-luminosity ELs are metal-rich and hence redder, whereas the low-luminosity ones are metal-poor and bluer. Thus the colours of ELs should be seen in the light of their metallicities. Figure 1 shows a plot of Mg index versus absolute magnitude (Mg–M) for 54 ELs for which data are available (Faber, 1973; Burstein, 1979; Terlevich *et al.*, 1981). The indices of Faber and Burstein were transformed to the scale of Terlevich *et al.*, using the galaxies common in their lists. Significantly, all the supernovic ELs have higher line-strength than expected from the mean Mg–M relationship. (The only exception is the interacting dwarf elliptical N 3226). In particular, the supernovic Virgo galaxies N 4374, 4486, and 4621, which are on an average 0.027 mag bluer in $(U-V)$, have 0.008 mag excess line-strength. If their colours were to reflect this excess metallicity, these galaxies should have been 0.04 mag redder than expected from the mean C–M relation. In other words, these supernovic ELs are 0.07 mag

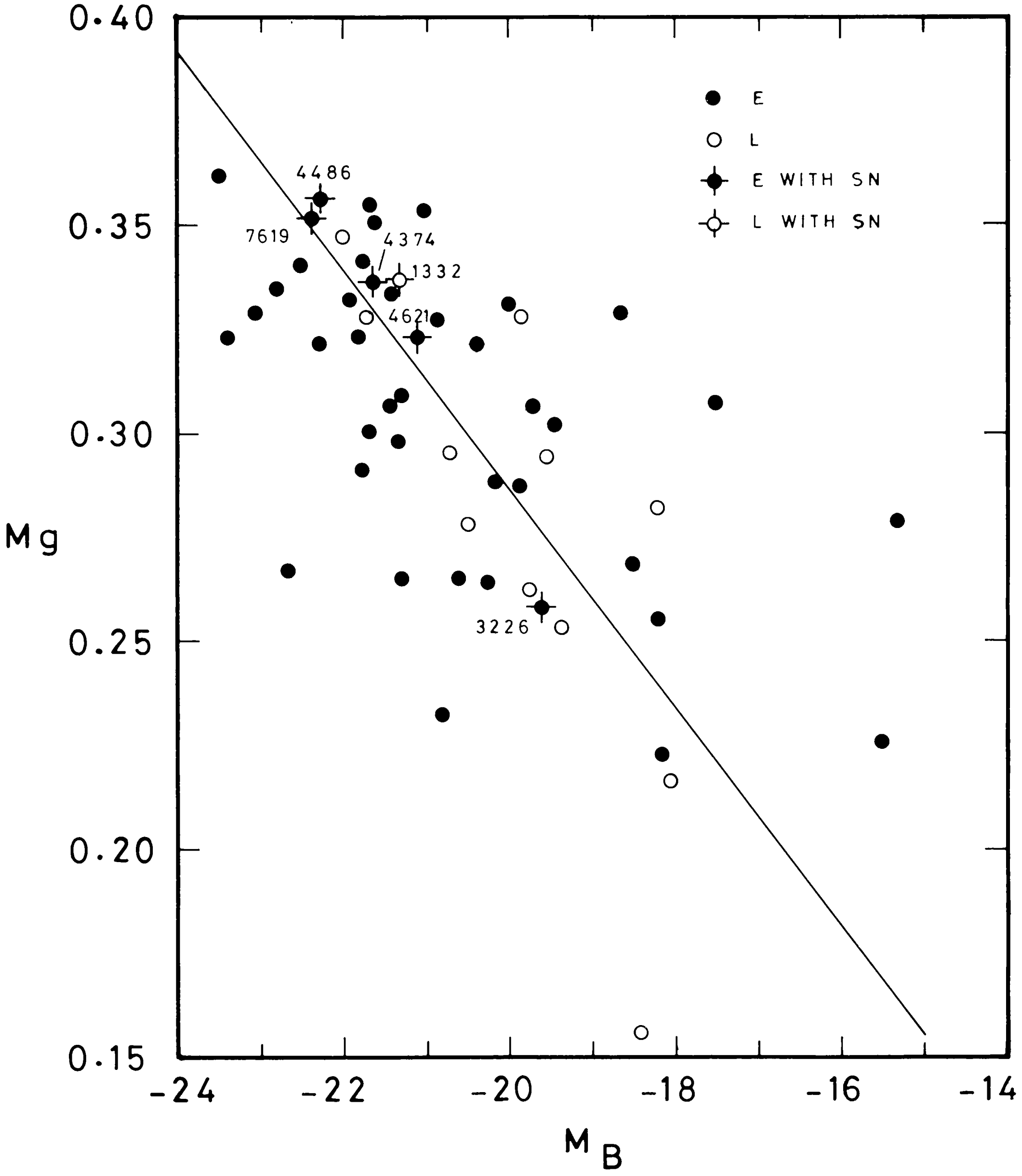

Fig. 1. The Mg-index-absolute magnitude diagram for EL galaxies. Supernovic ones are marked. The mean of the two regression lines between Mg and M_B is shown.

bluer than what they would have been if star formation had not occurred in them. Their excess metallicity may itself have resulted from such recurrent bursts of star formation. Furthermore, if these galaxies are dusty, the contribution of star formation to their colours would be higher than derived above.

Heckman (1983) finds evidence that radio-loud galaxies have higher metallicities than the radio-quiet ones. The metallicity parameter is 0.25±0.15 Å higher for the radio-detected galaxies, than for the ones not detected. There are nine supernovic ellipticals in his sample out of which three are not detected in the radio. The 'metallicity excess' for these galaxies is distributed between -0.26 Å (N 4486) and $+1.89$ Å (N 4564) with a mean value of $+0.59 \pm 0.62$ Å, more than twice the mean value for the radio-detected galaxies. The metallicity parameters for the three radio-quiet supernovic Es are distributed similar to the radio-detected ones. It would thus appear that the supernovic E are metal-richer in the mean compared to the entire sample of radio Es which, in turn has metallicities higher than the 'normal' Es.

Sandage and Visvanathan (1978b) find an unexplained intrinsic scatter of 0.06 mag in $(u-V)$-absolute magnitude diagram. We see from the above discussion that three mechanisms contribute to this scatter: the interstellar dust and increased metallicities would make the galaxies redder while the on-going star formation would make them bluer. The final colours would reflect the algebraic sum of these effects. In order to arrive at a rough estimate of the contribution due to star formation, we look at the observed value of $\Delta(u-V)_{0.5}^{\mathrm{KEM}}/\Delta(V-r)_{0.5}^{\mathrm{KEM}}$ tabulated by Sparks (1983). This ratio has a value of 1.4 ± 0.8 for the radio-detected galaxies in Sparks' sample. One expects a value of 2.7 if it had resulted from dust extinction and 12.2 if due to metallicity effects. The metallicity and star formation hardly affect the $(V-r)$ colours. Corresponding to the mean $\Delta(V-r) = 0.03$ observed by Sparks for radio Es, the dust extinction would require $\Delta(u-V) = 0.08$. Further, an increase in the Mg index by 0.01 mag would increase $\Delta(u-V)$ by 0.04 mag – as estimated from a comparison of the C–M and Mg–M relations. Thus, the higher metallicity and redenning due to dust should have made supernovic, radioloud E galaxies 0.12 mag redder in $(u-V)$. However, Sparks' radio-loud galaxies are only 0.05 mag redder and our sample of supernovic E is only 0.02 mag redder. This decrease in reddening should be attributed to star formation. The implied blue excess of 0.07–0.10 mag in these galaxies is consistent with our estimates above.

Finally, one should note that in order to obtain the standard colours of galaxies, one observes them at a given aperture, assumes a mean profile and then converts the observed colours to a standard aperture. If the star-forming regions lie outside the largest aperture employed, their contributions will not be taken into account. The majority of SN in Virgo ellipticals have indeed occurred outside the largest aperture used by Visvanathan and Sandage (1977). It should be possible to observe the colour excess due to localized star formation if multicolour surface photometric observations of regions around the recorded SN are made.

5. Conclusions

We have argued in favour of the assertion that all SNI come from short-lived stars. We have, however, suggested that all EL galaxies will not produce SN. Only if an EL galaxy accretes matter from outside and forms stars will it produce SN. Thus not all EL galaxies are 'supernovic'.

We have discussed some aspects of what may be termed the 'galactic ecology' – that is, the role of environment in determining the properties of an EL galaxy. We have argued that occurrence of supernovae and nuclear activity in elliptical galaxies are inter-related and a consequence of accretion of gas and star formation. In particular, we have shown that the supernovic Es are more than twice as likely to house a radio source as the non-supernovic ones; Moreover a supernovic galaxy is found atleast twice as often in a radio-loud sample, than in a radio-quiet sample.

We have discussed in some detail the question of the colours of supernovic ELs. We have argued that the spread in the C–M relation is governed by (a) interstellar dust, (b) star formation, and (c) metallicity of stellar population. While increasing dust and metallicity tend to make a galaxy redder, the star formation would make it bluer. Since the increase in metallicity results from several generations of star formation, and the dust is an indication of the availability of gas – particularly the processed matter – the three parameters are interrelated and help to reduce the scatter in the C–M relationship. The amount of star formation implied by the observed colours, after allowance is made for dust and metallicity, is consistent with the hypothesis that only about 30% of the ELs can produce SN. Seen in conjunction with the results of Sparks (1983), Heckman (1983), and Prabhu and Kochhar (1984) it appears that there exists a class of *rounder* ellipticals which have higher masses, mass-to-luminosity ratios, velocity dispersions, metalicities, and dust content. These ellipticals accrete gas, which forms stars fuelling the nuclear radio sources. Indeed an overwhelming majority of ellipticals in Table I are round. The radio-weak, *flatter* supernovic ellipticals NN 4564, 4621 deserve observations at increased resolution and sensitivity in order to examine whether they house compact nuclear radio sources or not. Also required are surface photometric investigations of supernovic ELs around regions of SN occurrence.

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