SUPERNOVAE IN EARLY-TYPE GALAXIES

R. K. KOCHHAR

Indian Institute of Astrophysics, Bangalore, India

Abstract. It is argued that all SNI come from short-lived stars and do not occur in a typical, isolationist, gas-free early-type galaxy. SNI occur only in those galaxies which accrete gas and form stars. SN properties of E/SOs are, therefore, determined by environmental factors. Presence of gas and dust in early-type galaxies, SN occurrence, nuclear emission, and radio-activity are all manifestations of the same phenomenon, namely availability of gas.

What is now urgently required is multi-colour photometry of supernovic early-type galaxies around the regions of recorded SN to see if there are signs of recent star-formation.

1. Introduction

Supernovae are empirically classified as of type I or type II depending on whether hydrogen lines are absent (SNI) or present (SNII) in the spectra near the light maximum. Very recently, SNI have been split into two subtypes, rather unimaginatively called Ia and Ib. The classical SNIa do not show helium lines, whereas some of the peculiar SNIb do. SNIb are about 1.5 mag underluminous compared to SNIa. Contrary to earlier belief SNIa are not all alike; nor are SNIb.

SNII and SNIb have a lot in common. Both occur only in spiral galaxies and are concentrated in the spiral arms. On the other hand the SNIa's occur in all types of galaxies, so that the supernovae in E, SO, and IO-type irregulars are exclusively of type Ia. Like the other types, SNIa in spiral are disc objects, but do not show any preference for the spiral arms. SNIa and Ib may occur with comparable frequency. Both SNI and SNII rates increase along the Hubble sequence (Branch, 1989).

2. SN Progenitors

The fact that SNII are confined to the spiral arms and other evidence tell us that their progenitors have initial masses $> 8\ M_{\odot}$.

If spirals were the only galaxies we knew of, then the facts that SNI are disc objects and their rate increases as we move to later, gas-rich spirals would lead to the conclusion that SNI are also associated with recent star formation. The conclusion finds support from the case of IO galaxies, which are early-type galaxies with evidence of recent large-scale star-formation. IOs are prolific SN-producers, five of them having produced eight recorded SN.

But SNI that is SNIa occur in E/SO galaxies also, which according to the conventional wisdom are featureless aggregates of old stars. SN in them must, therefore, come form low-mass stars.

Astrophysics and Space Science **157**: 305–314, 1989.

Currently the most favoured model for SNIa consists of a carbon-oxygen degenerate (COD) dwarf that accretes hydrogen-rich matter at an appropriate rate from its binary companion, crosses the Chandrasekhar mass limit and explodes by carbon deflagration (Nomoto, 1986). Such a binary would have come from intermediate mass stars but the time-scale of the SN explosion is determined by the evolutionary lifetime of the mass-donating companion. Thus in the case of the old-population-only ellipticals, this companion would be a low-mass star, whereas in the case of spirals it will have to be much more massive.

It is not clear whether this model can explain in a consistent manner the high SNIa rate in spirals. Indeed, Iben and Tutukov (1984) point out that the SNIa rate in our Galaxy according to this model is 5–10 times less than the predicted one. But the alternative scenario of the merger of two COD dwarfs is more likely to produce a neutron star than an SNI (Nomoto, 1986).

It is too early to have detailed models for SNIb. In Iben *et al.* (1987) an SNIb occurs as a consequence of mass transfer from a helium star to a COD dwarf. The minimum mass of the star progenitor is 2.3 $M_\odot$; so the model requires recent star formation but cannot explain among other things the concentration of SNIb in the spiral arms and the expectation that SNIa and Ib rates are comparable. Wheeler *et al.* (1987) believe that the progenitors of SNIb are suitably denuded cores of single stars of intermediate mass.

It is significant that SNIb, otherwise similar to SNIa, are closer to SNII as far as their location in spirals and progenitors are concerned.

We now revive the suggestion that SNIa also come from intermediate mass stars and are thus associated with recent star formation (Oemler and Tinsley, 1979; Kochhar and Prabhu, 1984; Kochhar, 1985). Then, a typical isolationist E/SO galaxy being gas-free does not form stars and will not produce SN. Only if the galaxy is so placed as to acquire gas and form stars in its main body will it produce SN. The absence of SNII in E/SO and IO galaxies then implies that stars $> 8\,M_\odot$ do not form in them.

Note that the star formation we are talking about occurs in the main body of the galaxy, where SN can be detected. Star-formation in the nuclear regions of the galaxies is an entirely different matter because SN events in these regions cannot be seen.

We thus introduce the concept of a supernovic E/SO galaxy, that is a galaxy producing SN in its main body. Of course, depending upon the rate of star formation, a supernovic E/SO may be more SN-prone than the others.

The sources of gas supply to a supernovic E/SO can be varied: a galaxy may accrete gas from its own halo (N4636); or from intracluster medium (N4486); or from a neighbouring galaxy (N3226). Alternatively or simultaneously, an E/SO may swallow gas clouds or gas-rich dwarf galaxies (N5128; N1316).

We note in passing that expressions like 'young' or 'old' SN, are rather dubious. A star's life, which may have been short or long, ends with a SN explosion. So there are no young or old SN; only SN with short-lived or long-lived progenitors.

It needs to be emphasized that our hypothesis of supernovic E/SOs is not inconsistent with the accreting white dwarf model for SNI. If SNIa occur in binaries, then our hypothesis suggests that these binaries formed in the recent past. Already there are suggestions that SNIa frequency in spirals requires a burst of binary star formation 10^{7-8} yr ago (Greggio and Renzini, 1983).

However, it should be noted that the essential requirement of a SNI model is a COD dwarf that grows in mass to the Chandrasekhar limit. The binary progenitor serves two purposes: (i) it removes the He–H envelope from the exploding star; and (ii) it sets the clock for SN events in E/SOs.

If such delaying tactics for E/SOs are not required, then the binary hypothesis loses its *raison d'être*: a single star with a COD core can explode as SNI (a and b) provided that it had lost its He–H envelope to the right extent. After all, single white dwarfs do manage to get rid of their envelopes.

Consider an intermediate mass star that forms a COD core. If it can manage to get rid of its He–H envelope before exploding, it will give rise to an SNIa. On the other hand, if it retains He envelope, the resulting event would be an SNIb. There is a possibility that in some cases some hydrogen would also be retained. The presence of hydrogen would immediately brand the event as SNII, which otherwise would be like an SNIb. SN 1957a in N2841 (Zwicky and Karpowicz, 1965) might be an example of a SNIb in SNII clothing.

We now examine evidence to support the assertion that SNI are indeed connected with signs of recent star formation.

3. Supernovic Galaxies

Recent astronomical advances have brought home the fact that the early-type galaxies are not as inactive as they had been made out to be. The notion that the early-type galaxies do not have gas or dust has been a matter of faith, so that any galaxy that showed any signs of life was immediately dubbed peculiar or irregular irrespective of the underlying stellar distribution.

It is, therefore, very instructive to look at the pathological cases of E/SO galaxies, classified as IO in RC2 (de Vaucouleurs *et al.*, 1976). Table I lists five IOs that have produced SN (see Barbon *et al.*, 1984, and later IAU circulars). It also gives their type according to RSA (Sandage and Tammann, 1981). Significantly, three of the five IOs have produced 2SN each. N3656 has a peculiar dark lane, and a diffuse arm and patch.

TABLE I

The supernovic IO galaxies

NGC	RSA	Remarks
2968	Amorph of SO pec	SN on bridge with N2970
3656^2	I	Arp 155 = VV22
4753^2	SO pec	IRAS galaxy
5195	SBO pec	Arp 85 = VV1 (with N5194)
5253^2	Amorph	Haro 10, member of 'Centaurus chain'

Superscript 2 denotes the occurrence of 2SN.

N4753 is an IRAS galaxy with some $10^8 M_\odot$ of cool matter (Jura, 1986). N5253 is a member of the group 'Centaurus chain', whose other members are the Sc galaxy N5236 (with five SN), the radio galaxy N5128 (= Cen A, with a recent SN), and the SO galaxy N5102. All these four galaxies appear to have accreted gas from a common envelope. This gas has led to star formation in the ellipsoidal galaxy N5253, enhanced the star formation rate in N5236, and fuelled the radio source in N5128. In N5102, a high H I content and young stellar population appear superposed on a normal SO; and there is photometric evidence for a burst of star formation some 10^8 years ago.

Further evidence for the prolificity of IO galaxies in producing SN comes from the Coma cluster. It has so far produced eight recorded SN, out of which two have occurred in IO galaxies (Thompson, 1981). Significantly all classified SN in IO galaxies are of type I.

The assertion that easy supply of gas leads to SN is further supported by other galaxies with two SN: N1316(E), 4874(E), and A1115 + 28(SO). N5874 lies at the centre of the Coma cluster and has access to intracluster gas. N1316 (Fornax A) lies in the outskirts of Fornax A cluster and is believed to have swallowed one, possibly many gas-rich companion galaxies.

A1115 + 28 (MCG 5–27–53) is an SO galaxy in the Zwicky cluster 156–14. It has a faint ring around it on which both the SN lie. This galaxy forms a pair (Holmberg 244) with the barred spiral MCG 5–27–52, 2 arc min away, which is presumably the source of gas for A1115 + 28.

In Table II we list the 12 SOs that have produced SN. Significantly eight of these carry the tag peculiar, doubtful or uncertain as far as their classification is considered (denoted by an asterisk in the table). Six out of these 12 SOs are interacting galaxies, again highlighting the role of gas supply in SN production.

TABLE II

Supernovic SO galaxies

NGC	Remarks
*1332	Pair with N1331
*1411	–
3570	–
4340	Ho 391b. Pair with N4350
*4382	Ho 397a. Pair with N4394
*4410B	Close pair with 4410A Common envelope
*4526	–
*4887	–
*5485	Pair with N5484
5854	–
*6835	Pair with N6836
7634	–

* denotes peculiarity, doubt or uncertainty in RC2 classification.

1989Ap&SS.157..305K

The 16 supernovic Es are listed in Table IV and discussed in Section 7. Following the recent practice, we have included the active galaxies N1275, 1316, and 5128 among ellipticals. There is no unanimity regarding their classification. N1275 is Pec (RC2) or E pec (RSA); N1316 is SO pec (RC2) or Sa pec (RSA): N5128 is SO pec (RC2) or SO + S pec (RSA). Both the sources of course agree that all three are peculiar. Three more galaxies in Table IV are peculiar according to RC2 (N3226, 4486, 4782).

4. Outlying SN

Many SN have occurred outside the optical radius of the galaxy. Table III lists some candidates in NGC galaxies. Note that N4374 and 4406 are X-ray bright galaxies in the core of Virgo cluster (Figure 1) with N4374 already having produced an SN. SN 1980i implies star formation at large distances from galaxy centres (Sarazin, 1986). Significantly all these outlying SN are of type I.

TABLE III

Some outlying SN

SN	NGC (type)	Δ/R	Remark	Ref.
1980i	2968–70 (IO–E)	2.9	SN on intergalactic bridge	1
1971c	3904 (E)	4.5	Galaxy pair with N3293	1
1980i	4374–4406 (E–E)	3.1–2.5	SN 50 kpc from each galaxy on intergalactic bridge and in the hot halo of N4460	2
1956b	4782–3 (E–E)	1.6		1
1970j	7619 (E)	1.1		1

Δ = radial distance of SN from the galaxy centre.
R = optical radius of the galaxy.
References:
(1) Tammann (1974).(2) Smith (1981); Forman *et al.* (1985).

5. X-Ray Data and SN

Halos of hot gas around early-type galaxies are best interpreted in terms of gravitational heating of gas shed in the course of normal stellar evolution, provided the SNI rate be at least a factor of three lower than the Tammann (1974) value of 0.22 (Sarazin, 1986).

It is not at all clear how the SNI rate can be unilaterally lowered. But the problem of X-ray heating finds a natural explanation in terms of our hypothesis that SNI are associated with recent star formation.

The interstellar gas is heated by gravitational processes and forms a halo around the galaxy. Part of it becomes thermally unstable and forms dense, cool lumps from which stars $< 8\,M_{\odot}$ form. Now, since SN are occurring in regions of high gas density, the SN

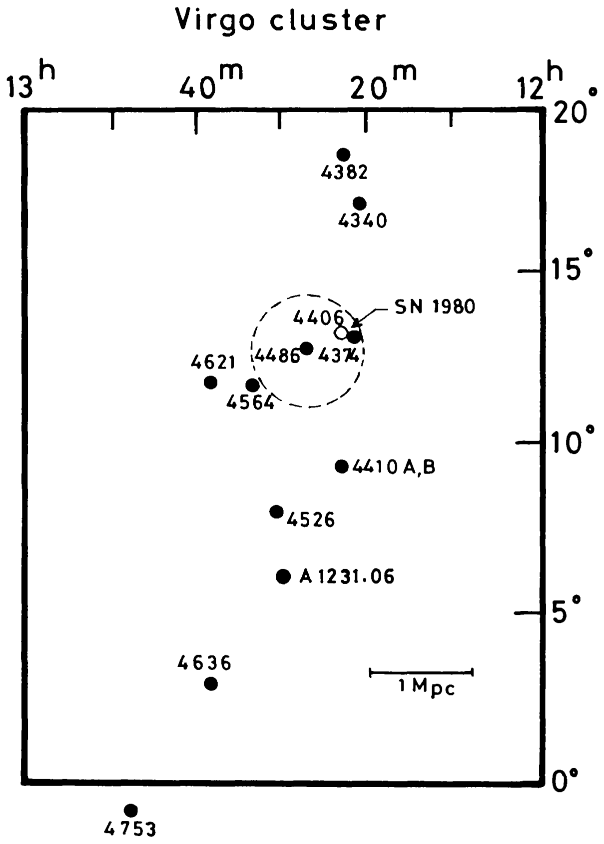

Fig. 1. The supernovic E/SOs in the Virgo region. The numbers are the NGC numbers. The inner circle denotes the high-density core of the cluster.

TABLE IV

Supernovic ellipticals

NGC	H I	Dust	Ionized gas	Radio	X-ray	Inter-acting	Remarks
1275 Per A			√	√	√		SN in region of low-velocity filaments
1316 For A			√	√	√		Two SN
2672						√	Arp 1678. Pair with 2673
3226			√			√	Arp 94 = VV209. Pair with 3227
3904	√					√	Pair with 3293. SN outlying
4335							
4373 Vir[a]		√	√	√	√		
4486 Vir A			√	√	√		
4564 Vir							
4621 Vir							
4636 Vir			√	√	√		
4782				√		√	VV201. Pair with 4783 SN outlying
4874 Com				√			Two SN
5128 Cen A	√	√	√	√	?		SN in the dust band
7619 Peg I				√	√		SN outlying
7768							

[a] SN 1980i appeared on N4374's material bridge to N4406. The SN is within the X-ray halo of N4406.

energy would not contribute to the X-ray luminosity but would be dissipated or radiated outside the X-ray band, leaving gravitational heating as the sole mechanism responsible for the X-ray heating of the gas.

6. Environmental Effects: Galactic Ecology

If SNIa came from a normal population of E/SO galaxies, then the SN rate in them should not be connected with environmental effects. But this is not the case. Galactic ecology is an important factor in determining the SN properties of the early-type galaxies.

The Virgo and Coma clusters provide evidence in support of the accretion hypothesis. The Virgo region ($12^h < \mathrm{RA} < 13^h$; $0 < \mathrm{Dec} < 20°$) contains only 11% of NGC galaxies, but accounts for 30% of the supernovic E/SOs. This shows that the Virgo E/SOs are thrice as prolific SN-producers as the general sample of E/SOs. (SN yield does not seem to depend upon the search intensity; cf. Tammann, 1974.)

The reason for this is that Virgo E/SOs carry individual gas reservoirs around them in the shape of hot halos from which they can accrete gas and form stars. Within the high-density core of the Virgo cluster three SN have occurred (see Figure 1).

As against Virgo, the hot gas in the compact, dynamically evolved, spiral-poor Coma cluster is associated with the cluster as a whole and not with any individual galaxy. That would explain why the SN rate in Coma is a factor of three smaller than in Virgo (Barbon, 1978). The 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 would expect the supernovic ellipticals to have the same distribution as the galaxies in general. This, however, is not the case. All supernovic E/SOs in Coma are confined to a plane (Figure 2). Presumably, some gas in Coma has settled down in a disc and is available for accretion by the galaxies there, giving rise to star formation and SN, converting in the process two early-type galaxies into IOs.

7. Correlations

We have argued that the occurrence of SN E/SOs depends up on the availability of gas to form stars. This gas may come from the galaxy's own X-ray halo, or from outside. The cool gas would lead to some features in the galaxy. When the gas eventually reaches the centre, it can lead to optical nuclear emission and radio emission.

From among the bright elliptical galaxies, radio-emitters are 20–25% (Hummel *et al.*, 1983; Dressel and Condon, 1978): H I detections 15% (Knapp *et al.*, 1985); dust 36% (Ebneter *et al.*, 1988). The frequency of nuclear optical emission is about 30% (Bettoni and Buson, 1987; and references given therein). Note that the samples involved in each case are different, and the percentages are only indicative. X-ray, IR, and UV studies have been made only of selected galaxies.

Various correlations have already been established. In a general Westerbork sample,

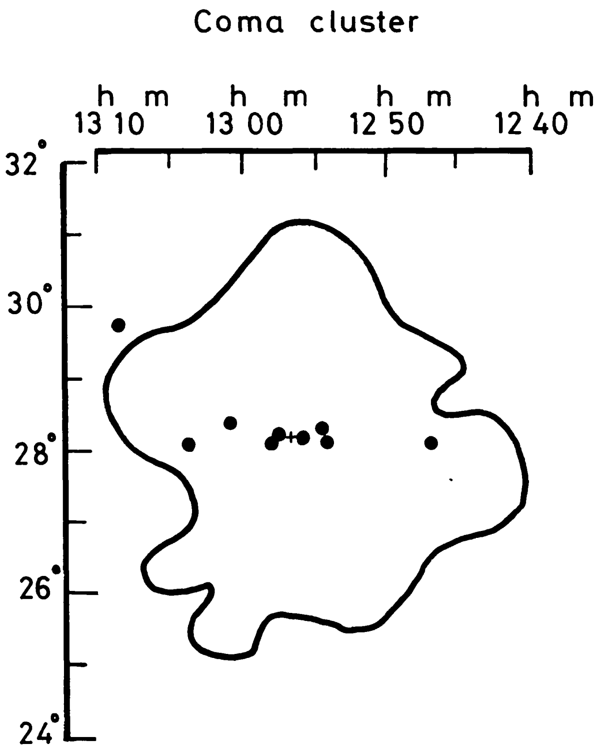

Fig. 2. The supersonic galaxies in the Coma cluster (Barbon, 1978).

20% of the ellipticals are radio emitters. But in the subsample of emission-line galaxies, the fraction of radio-detected galaxies is 30%. If we consider the sample of radio galaxies, then 58% of the galaxies show emission lines, while in a general sample, the fraction is only 31%. There is also a significant correlation between the presence of dust and radio emissions: 59% of dusty ellipticals and 52% of the SOs are radio loud (Bettoni and Buson, 1987).

The correlation between radio-activity and H I is already well attested. Hummel (1980) has shown that ellipticals with detected H I are much more likely to contain nuclear emission than ellipticals without H I. Shostak *et al.* (1983) have found that the H I detection rate in radio galaxies is consistent with the presence of thin H I disc of galactic dimensions in all radio galaxies.

Fabbiano *et al.* (1987) have shown from a sample of 28 E/SOs that the radio and X-ray luminosities are correlated.

Because of the small number of SNI known, it is not always possible to correlate SN occurrence with other activities, especially becuase most of the recent spectroscopic studies are of the southern skies, whereas supernovic galaxies are mostly in the north. Figure 3 shows that the fraction of radio emitters in a subsample of supernovic ellipticals is much higher than in the general sample. The numbers involved are small, but the trend is unmistakable. In view of the correlation of radio property with other properties, one concludes that SN activity is related to the others.

Table III lists the 16 supernovic ellipticals and their properties (see Barbon *et al.*, 1984). The list includes such well-known galaxies as N1275, 1316, 4486, and 5128.

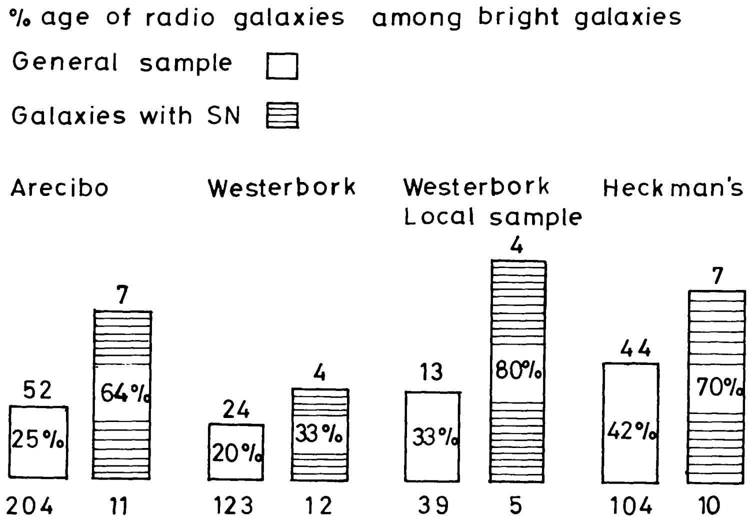

Fig. 3. The percentages of radio galaxies in samples of bright galaxies and in subsamples of bright supernovic galaxies. Heckman's sample pertains to detections only. (Arecibo: Dressel and Condon, 1978; Westerbork: Hummel *et al.*, 1983; Heckman's: Heckman, 1983.)

Four of the 16 galaxies form pairs with other galaxies which presumably are the suppliers of the gas. An additional six (excluding N5128) show hot gas which cools to form stars.

Seven of our galaxies figure in Bettoni and Buson's (1987) *Catalogue of Early-Type Galaxies with Emission Lines* and significantly all seven show emission lines as well as radio emission.

In fact, 12 out of 16 galaxies show one activity or the other. Two of the remaining four (N4564 and 4621) are in the Virgo cluster. There are only two galaxies N4335 and 7768 whose only claim to fame so far has been the occurrence of SN. They certainly deserve a second look.

8. Colours of Supernovic Ellipticals

If SNI come from short-lived stars, then the E/SO galaxies with SN would be expected to be bluer than the others. This, however, is not the case. A sample of 354 E/SOs has $U - V_{0.5}^{\mathrm{KEM}}$ of 2.33 ± 0.09 (Sandage and Visvanathan, 1978). Out of this sample 12 Es and 8 SOs have produced SN; in their case the value is 2.35 ± 0.05, not significantly different from the whole sample (the very blue galaxy N4382 with $U - V_{0.5}^{\mathrm{KEM}} = 2.08$ has been excluded).

The colour of a supernovic E/SO is contributed to by three factors: (i) the blueness due to star formation; (ii) the reddening due to dust, and (iii) the redness due to high metallicity (Kochhar and Prabhu, 1984). It is conceivable that these three factors cancel out.

It is relevant to recall that the standard colours of galaxies are obtained by observing them at a given aperture. If the star-forming regions lie outside the largest aperture employed; their contribution will not be taken into account. The majority of SN in the

Virgo E/SOs have indeed occurred outside the largest apertures used by Sandage and Visvanathan.

What is required is multi-colour surface photometry of the regions around the SN to see if these regions show signs of star formation.

Acknowledgements

This paper is based on the work done in collaboration with T. P. Prabhu. I thank Drs Alvio Renzini, Roberto Terlevich, Dave Branch, and Ismael Perez-Fournon for helpful discussions during the conference.

References

Barbon, R.: 1978, *Astron. J.* **83**, 13.
Barbon, R., Cappellaro, E., Ciatti, F., Turatto, M., and Kowal, C. T.: 1984, *Astron. Astrophys. Suppl. Ser.* **58**, 735.
Bettoni, D. and Buson, L. M.: 1987, *Astron. Astrophys. Suppl. Ser.* **67**, 341.
Branch, D.: 1989, in J. Beckmann (ed.), *Evolutionary Phenomena in Galaxies*, Cambridge Univ. Press, Cambridge.
de Vaucouleurs, G., de Vaucouleurs, A., and Corwin, H. G.: 1976, *Second Reference Catalogue of Bright Galaxies*, Univ. of Texas, Austin (RC2).
Dressel, L. L. and Condon, J. J.: 1978, *Astrophys. J. Suppl. Ser.* **36**, 53.
Ebneter, K., Djorgovski, S., and Davis, M.: 1988, *Astron. J.* **95**, 422.
Fabbiano, G., Klein, U., Trinchieri, G., and Wielebinski, R.: 1987, *Astrophys. J.* **312**, 111.
Forman, W., Jones, C., and Tucker, W.: 1985, *Astrophys. J.* **293**, 102.
Greggio, L. and Renzini, A.: 1983, *Astron. Astrophys.* **118**, 217.
Heckman, T. M.: 1983, *Astrophys. J.* **273**, 505.
Hummel, E.: 1980, Ph.D. Thesis, Univ. of Groningen.
Hummel, E., Kotanyi, C. G., and Ekers, R. D.: 1983, *Astron. Astrophys.* **127**, 205.
Iben, I. and Tutukov, A. V.: 1984, *Astrophys. J. Suppl. Ser.* **54**, 335.
Iben, I., Nomoto, K., Tornambè, A., and Tutukov, A. V.: 1987,, *Astrophys. J.* **317**, 717.
Jura, M.: 1986, *Astrophys. J.* **306**, 483.
Knapp, G. R., Turner, E. L., and Cunniffe, P. E.: 1985, *Astron. J.* **90**, 454.
Kochhar, R. K.: 1985, in G. Srinivasan and V. Radhakrishnan (eds.), *Supernovae, Their Progenitors and Remnants,* Indian Acad. Sci., Bangalore.
Kochhar, R. K. and Prabhu, T. P.: 1984, *Astrophys. Space Sci.* **100**, 369.
Nomoto, K.: 1986, *Ann. N.Y. Acad. Sci.* **470**, 294.
Oemler, A. and Tinsley, B. M.: 1979, *Astron. J.* **84**, 985.
Sandage, A. and Tammann, G. A.: 1981, *A Revised Shapley–Ames Catalog of Bright Galaxies*, Carnegie Institution (RSA).
Sandage, A. and Visvanathan, N.: 1978, *Astrophys. J.* **225**, 742.
Sarazin, C. L.: 1986, in J. L. Bregman and F. J. Lockman (eds.), *Gaseous Halos of Galaxies*, NRAO.
Shostak, G. S., van Gorkom, J. H., Ekers, R. D., Sanders, R. H., Goss, W. M., and Cornwell, T. J.: 1983, *Astron. Astrophys.* **119**, L3.
Smith, H. A.: 1981, *Astron. J.* **86**, 998.
Tammann, G. A.: 1974, in C. B. Cosmovici (ed.), *Supernovae and Supernova Remnants*, D. Reidel Publ. Co., Dordrecht, Holland.
Thompson, L. A.: 1981, *Publ. Astron. Soc. Pacific* **93**, 176.
Wheeler, J. C., Harkness, R. P., Barker, E. S., Cochran, A. L., Wills, B. J., and Wills, D.: 1987, *Astrophys. J.* **313**, L69.
Zwicky, F. and Karpowicz, M.: 1965, *Astron. J.* **70**, 564.