On core-collapse supernovae in normal and in Seyfert galaxies

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ABSTRACT

This paper estimates the relative frequency of different types of core-collapse supernovae, in terms of the ratio $S$ between the number of Type Ib–Ic and of Type II supernovae. We estimate $S$ independently for all normal and Seyfert galaxies whose radial velocity is $v_r < 14,000 \text{ km s}^{-1}$, and which had at least one supernova event recorded in the Asiago catalogue from 1986 January to 2000 August. We find that the ratio $S$ is $\approx 0.23 \pm 0.05$ in normal galaxies. This value is consistent with constant star formation rate and with a Salpeter initial mass function and an average binary rate of $\approx 50$ per cent. On the contrary, Seyfert galaxies exceed the ratio $S$ in normal galaxies by a factor of $\approx 4$ at a confidence level of $2 \sigma$. A caveat is that the numbers for Seyferts are still small (six of Type Ib–Ic and six of Type II supernovae discovered as yet). Assumed to be real, this excess of Type Ib/c supernovae may indicate a burst of low-age star formation ($\tau \approx 20 \text{ Myr}$), a high incidence of binary systems in the inner regions ($r < 0.4 \text{ R}_25$) of Seyfert galaxies, or a top-loaded mass function.

Key words: stars: formation – supernovae: general – galaxies: nuclei – galaxies: Seyfert – galaxies: starburst – galaxies: stellar content.

1 INTRODUCTION

The relationship between circumnuclear star formation and non-thermal nuclear activity is as yet poorly understood. While the possibility that non-thermal activity may be entirely ascribed to massive stars and to supernova events (Terlevich et al. 1993) is challenged by several lines of evidence, it is unlikely that the onset of nuclear activity and strong nuclear or circumnuclear star formation can be fully unrelated phenomena. Supernovae may not be responsible for the optical spectrum and emission line of Seyfert 1 galaxies, but reprocessed gas of supernova ejections may eventually be accreted by the central black hole, influencing the opacity and hence the radiating properties of the accretion disc, which is reputed to be one of the ultimate components of the active galactic nucleus (AGN) central engine.

Core-collapse supernovae from massive progenitors, albeit rare events, are diagnostics of recent star formation. The aim of this paper is to estimate the ratio between the total number of Type Ib/c and Type II supernovae [$S = N(\text{Ib/c})/N(\text{II})$] discovered in a suitable sample of non-active (hereafter normal) galaxies, as well as to compare it to that of Seyfert galaxies. As we will show through this paper, the ratio $S$ reflects metallicity, age, fraction of binary systems, and initial mass function (IMF) shape effects, which are probably much different in normal and (at least in some) Seyfert galaxies.

2 SAMPLE SELECTION AND CRITERION

We cross-correlated the latest available Asiago Supernova Catalogue (last supernova recorded: 2000di on August 23; Barbon et al. 1993) with the 9th edition of ‘A Catalogue of Quasars and Active Galactic Nuclei’ by Véron-Cetty & Véron (2000). All AGN hosting a supernova have $v_r \leq 14,000 \text{ km s}^{-1}$. A temporal restriction is needed as Type Ib and Ic supernovae, first observed in the 1960s (Bertola 1964) were labelled as peculiar ‘Type I’ supernovae for more than two decades. The realization that they are a different class of objects came in around 1985 (Elias et al. 1985; Panagia, Sramek & Weiler 1986; Porter & Filippenko 1987). We limit our counts to supernovae discovered after 1985 December 31. Only few identification of Type Ib/c supernovae discovered earlier than 1986 January 1 are available (as a product of subsequent re-identification of older Type I spectra).

We define a sample of ‘normal’ galaxies as including all galaxies listed in the Asiago Catalogue with $v_r \leq 14,000 \text{ km s}^{-1}$, not classified as Seyfert (including uncertain Seyfert types, coded as ‘S’), HII (code H2) or LINERs (code S3) in the Véron-Cetty & Véron (2000) lists. The Seyfert sample comprises all Seyfert galaxies as above but coded as S1, S2 or S1x in the catalogue (see Table 1 for sample sizes).
We restrict our comparison to the rate of Type Ib–Ic and II supernovae, because the control time \( t_c \) is approximately the same for both Type Ib/c and Type II supernovae. The difference in brightness and light curve shape between Type Ib–Ic and Type II supernovae would translate in a \( \Delta t_c/t_c \approx 15 \) per cent (Cappellaro et al. 1993), which is marginal with respect to the magnitude of the effects we are considering (a factor \( \approx 4 \); see Section 3). Even if Seyfert galaxies and normal galaxies have been monitored over different times, and with different techniques, the ratio \( N(\text{Ib/c})/N(\text{II}) \) should almost reproduce the true ratio of supernova rates for Type Ib/c and Type II (but clearly not each supernova rate in supernova units). In other words, we have \( \text{S}\equiv\text{S}_{\text{Ib/c}}/\text{S}_{\text{II}}=\text{S}/\text{S}_{\text{Ib/c}}=\text{S}/\text{S}_{\text{II}} \), where \( \text{S} \) is in centuries, \( \text{S}_{\text{Ib/c}} \) is expressed in number of supernovae per year, and \( \text{S}_{\text{II}} \) is expressed in supernovae per year, and \( \text{S}/\text{S}_{\text{Ib/c}} \). Selection effects, described in the next section, will operate in the same way in both galaxy samples.

The Seyfert sample is dominated by Seyfert 2 galaxies, and at any rate by very low luminosity AGN. The average absolute magnitude of the Seyfert 2 sample is \( M_b \approx -19.1 \) (taking data from Véron-Cetty & Véron 2000). The S1x nuclei are, on average, of similar luminosity (\( M_b \approx -19.3 \)). In complete samples, Seyfert 1 nuclei are on average a factor of 100 brighter than Seyfert 2 (see also Section 5).

## 3 RESULTS

### 3.1 The distribution of core-collapse supernova types

Table 1 reports the number of supernovae counted in each sample, with the restrictions on redshift and on discovery time motivated in the previous section.

The ratio \( S = N(\text{Ib–Ic})/N(\text{II}) \) for normal galaxies is \( \approx 0.23 \), very close to the values obtained from the ratio of absolute supernova rates in supernova units (SNe): 0.18 for S0a–Sb galaxies, and 0.27 for Sbc–Sd galaxies (Cappellaro et al. 1997). The ratio \( S \) is much larger in the Seyfert than in the normal galaxy samples, by a factor \( \approx 4 \). \( S_{\text{Seyfert}} = N(\text{Ib–Ic})/N(\text{II}) \approx 0.5 \approx S_{\text{Norm}} \approx 0.19 \), where \( N(\text{Ib–Ic}) = N(\text{Ib}) + N(\text{Ic}) + N(\text{II}) \) is the number of core-collapse supernovae. Assumption of binomial statistics, where the probability is \( p = S_{\text{Seyfert}} \), yields an excess of Type Ib–Ic supernova in the Seyfert sample significant to a confidence level of \( \approx 2 \sigma \) [\( N(\text{Ib/c}) \) expected in the Seyfert sample is \( 2.3 \pm 1.3 \)]. However, this simple estimate may not be fully satisfactory, as normal galaxies and Seyfert samples may be influenced by factors affecting the probability of discovery as well as the intrinsic rate of supernova explosion (see Section 3.3).

### 3.2 The radial distribution of supernovae

Fig. 1 shows the distribution of the supernova de-projected distance \( d^\phi \) normalized to the standard isophotal diameter \( D_{25} \), for normal and Seyfert galaxies, computed under the assumptions that all galaxies can be considered as flat discs. Supernovae in Seyfert galaxies show a tendency to occur closer to the nucleus. A Kolmogorov–Smirnov test suggests that the distributions are different to a statistical significance of 0.999. This result has been known for some time (Petrosian & Turatto 1990; Kazarian 1997) from the analysis of supernova data in different samples.

### 3.3 Significance of results: is there any real excess of Type Ib–Ic supernovae in Seyfert galaxies?

The ratio \( S_{\text{Norm}} \) has been determined from 210 Type II and 48 Type Ib–Ic supernovae; therefore it is possible to safely use the binomial statistics to write \( S_{\text{Norm}} = 0.23 \pm 0.05 \) (at \( 1 \sigma \) confidence level). To properly estimate the statistical significance of the excess of Type Ib–Ic supernovae in Seyfert galaxies, we used a ‘bootstrap’ method. We generated a large number (\( \approx 10^3 \)) of synthetic data sets matching the Seyfert galaxy sample. The synthetic data set were extracted randomly from our normal galaxies samples, with the same number of galaxies as in the Seyfert samples, and with the same distribution of any parameter influencing either the probability of discovery of supernovae, or the intrinsic rate of supernova production (Cappellaro et al. 1993): (i) galaxy inclination, (ii) \( D_{25} \), (iii) morphological type, (iv) radial velocity. ‘Matching’ samples were considered as all the synthetic samples for which none of the four distributions were statistically different from the distributions for the Seyfert sample at a \( 2 \sigma \) confidence level. In other words, as we could not eliminate selection effects
from our Seyfert sample, we reproduced them in a similar fashion in a large number of ‘pseudo-control samples’.

In all cases save the morphological type, the statistical difference between the parameter distribution of the Seyfert galaxy sample and of same-size samples of normal galaxies was assessed by a Kolmogorov–Smirnov test. In the case of morphological type, a \( \chi^2 \) test was applied, after rebinning of \( T \) values into four bins for early type galaxies (E–S0), early spirals (S0a–Sb), late-type galaxies (Sc and later) and unknown or peculiar. We computed the number of supernovae for each synthetic data set, and then we counted which fraction of synthetic data sets had supernova numbers exceeding the number from the real data. That fraction has been assumed to be our statistical significance (Efron & Tibshirani 1993).

In Fig. 2 the thick solid line shows the distribution of \( S \) for the pseudo-control samples. The dot-dashed line marks the value found for the Seyfert sample. Only in \( \approx 1 \) per cent of the cases a larger value of the ratio \( N(\text{Ib/c})/N(\text{II}) \) is found, confirming that a realistic estimate of the significance of the result is \( \approx 2\sigma \). The thin line marks the distribution of supernovae after supernovae whose classification was unknown and or of generic type ‘I’ have been reassigned (consistent with the approach of Petrosian & Turatto 1990). From Fig. 2, we infer that the redistribution for unclassified supernova types has a negligible effect on the statistical results.

### 4 INFERENCES ON STAR FORMATION

#### 4.1 Normal galaxies

The interpretation of the ratio \( S \) for the ‘average normal’ galaxy is straightforward, if we consider it most likely that Ib/c supernovae progenitors are Wolf–Rayet stars, whose hydrogen envelope has been fully lost (Filippenko 1998, and references therein). The latter stars may result from the evolution of the most massive stars \( (M \approx 40 \text{ } M_\odot) \); Bressan, Chiosi & Bertelli 1981; Bressan 1994) or from the less massive primary component of binary systems after the mass transfer (e.g. table 2 of Wellstein & Langer 1999).

Figure 2. Distribution of the ratio \( \hat{S} = N(\text{Ib/c})/N(\text{II}) \) for 20000 bootstrap replications of the Seyfert sample by pseudo-control samples of the same size (see text). Thick solid lines: without redistribution of unknown and Type I supernovae; thin solid line: after redistribution of unknown and Type I supernovae. We considered 25 galaxies with \( v_e \leq 14000 \text{ km s}^{-1} \) with supernovae discovered during or after 1985. The vertical dot-dashed line marks the value found for the Seyfert sample, as reported in Table 1.

Figure 3. Upper panel: expected ratio \( \hat{S} \) of SNIbc to SNII rates as a function of the binary fraction. A Salpeter IMF and a constant star formation rate in the last 100 Myr have been adopted. Several cases are considered as detailed in the text. Middle panel: IMF effects. Ratio \( \hat{S} \) in case (iii), for different IMF exponents \( x \), as labelled in the figure. The Salpeter IMF corresponds to \( x = 1.35 \). Lower panel: age effects. Ratio \( \hat{S} \) in case (iii) for different starburst ages (assuming solar composition), as labelled in Myr.

Assuming a constant star formation rate during the last 100 Myr, and adopting the same initial mass function (IMF) for single stars and binary components, the ratio \( \hat{S} \) is simply given by

\[
\hat{S} = \frac{\sum_i W_i \int_{m_i}^{m_i^{\text{Ibc}}} \psi(m) \, dm}{\sum_j W_j \int_{m_j}^{m_j^{\text{II}}} \psi(m) \, dm},
\]

where \( m \) is the initial mass of the star, the index \( i \) refers to all channels leading to Type Ib/c supernovae, \( j \) to the formation of Type II supernovae and the \( W \) terms are the relative weights that depend on the overall binary fraction and on the relative frequency of case A, B and C in the binary evolution.

The expected variation of the ratio \( \hat{S} \) is shown in the upper panel of Fig. 3, as a function of the binary fraction. To this purpose we have adopted a Salpeter IMF up to \( 120 \text{ } M_\odot \), and the values of \( m_i^{\text{Ibc}} \) and \( m_j^{\text{II}} \) were taken from table 2 of Wellstein & Langer (1999); the latter authors also assume that all stars more massive than \( 40 \text{ } M_\odot \) explode as Type Ib/c supernovae, while single stars and secondary stars less massive than \( 40 \text{ } M_\odot \) explode as Type II supernovae. We have considered several cases: (i) all binaries evolve as Case A (dotted line); (ii) all binaries evolve as Case B (dashed line); (iii) Case A and B share the same relative weight (solid line); (iv) as in (iii) but in the case that only binary members explode as Type Ib/c supernovae (lower dot-long-dashed line); and (v) as in (iii) but in this case the initial mass for Ib/c supernovae has been lowered from \( 40 \text{ } M_\odot \) to \( 25 \text{ } M_\odot \) (upper dot-short-dashed line). The horizontal line represents the observed average value for the normal galaxy sample (CS). We did not account for Case C evolution because it is
considered to be a very rare event and as such it will only slightly modify the picture depicted in Fig. 3. The fraction \( S \) does not appear much affected by the precise details of the binary evolution. For normal spirals, the observed ratio is consistent with a scenario where the progenitors of Type Ib/c supernovae are Wolf–Rayet stars, either evolved from stars initially more massive than 40 \( M_\odot \) or from less massive primary components of binary systems. The data support a universal Salpeter IMF and indicate a binary fraction of about 50 per cent. A significantly higher binary fraction (about 75 per cent) is required if one insists that only binary evolution gives rise to Type Ib/c supernovae. As discussed by Wellstein & Langer (1999), uncertainties in the mass-loss rate, convection treatment and chemical composition may affect both the upper mass limit (40 \( M_\odot \)) leading to Type II supernovae in single stars, and the mass transfer phase in binary evolution. Fortunately, uncertainties leading to different Type Ib and type Ic supernovae events are not relevant here, because we are considering their combined frequency.

4.2 Seyfert galaxies

From Table 1 and Fig. 3, we also infer that things could be markedly different in Seyfert galaxies, where the observed ratio is \( S \approx 1 \). Several Seyfert galaxies, of which a sizeable fraction belongs to strongly interacting systems (≈2/3 of Seyfert 2; Dultzin-Hacyan et al. 1999), show significant, or even dominant (over the active nucleus luminosity) circumnuclear star formation. A recent H\( \alpha \) narrow-band survey (González-Delgado, Heckman & Leitherer 2001) found that about 1/2 of Seyfert 1 and Seyfert 2 show maximum values of H\( \alpha \) region emission in the circumnuclear regions. This study of the radial distribution of H\( \alpha \) regions in normal, LINER and Seyfert galaxies agrees with a large number of detailed spectroscopic and imaging studies of Seyfert galaxies. Consistently, the radial distribution of supernovae appears to be more strongly peaked in Seyfert galaxies than in normal galaxies in several samples (Petrosian & Turatto 1990; Kazarian 1997) as well as in our own. However, enhancement of the star formation rate in the inner galactic regions cannot explain the relative excess of Type Ib/c supernovae found in Seyfert galaxies.

The observed radial gradients of chemical composition (Vila-Costas & Edmunds 1992) and the central concentration of Type Ib/c supernovae in Seyfert galaxies (Fig. 1) imply that Ib/c supernovae could be typically produced in 2Z\( \odot \) regions in Seyfert and in Z\( \odot \) regions in normal galaxies. Because mass loss increases with metallicity and, consequently, the minimum initial mass for single Wolf–Rayet production decreases, \( S \) could be a function of metallicity. As shown by case (iv) in the upper panel of Fig. 3, \( S \) could increase by the 100 per cent if the minimum mass for Ib/c production decreases from 40 to 25 \( M_\odot \). However, this is not very likely because mass loss is also sensitive to the luminosity and the latter is a strong function of the initial mass (Bressan 1994).

Another possible explanation is that star formation in circumnuclear and disc regions of Seyfert galaxies is a high binary fraction. If we assume that all young stars are in binaries and undergo mass transfer during their life, we would obtain \( S = 0.6 \). This value, though lower than the observed one, would double the expected relative frequency of binary stars with respect to the normal galaxies. Inspection of Table 1 shows that the observed ratio \( N(\text{Ia})/N_{\odot} \) is 0.63 for the normal galaxies and rises to 1 in the Seyfert sample. If this ratio was free from selection effects, it would strongly indicate a larger probability of assembling binary systems. However, the magnitude at maximum and the light curve of type Ia supernovae is very different from that of core-collapse supernovae. This makes the comparison of the ratio \( N(\text{Ia}) \) over a number of core-collapse supernovae meaningless if it is not accompanied by a careful examination of the relative control times which, unfortunately, cannot be done here.

An appealing alternative is constituted by a ‘top-loaded’ IMF. The high efficiency at which gas is reprocessed into stars is often taken as an indication in favour of a top-heavy initial mass function in compact starbursts, e.g. Franceschini (1999). The middle panel of Fig. 3 depicts the effect of changing the IMF exponent \( x \), where \( \psi(m) \propto m^{-1.5} \) and \( x = 1.35 \) corresponds to the Salpeter IMF. The value of \( S \) increases as the IMF becomes flatter. The observed value in Seyfert galaxies would indicate a very flat IMF, above 8 \( M_\odot \). We must however stress that conclusive evidence in favor of an IMF slope significantly flatter than the Salpeter one has not been found in external galaxies, not even in Wolf-Rayet and Starburst galaxies (Schaerer, Contini & Kunth 1999; Leitherer 1999).

The necessity of a top-heavy IMF disappears if, in Seyferts, we are observing a very young burst of star formation. To illustrate this effect we show the run of the ratio \( S \) with the binary fraction for different burst ages and a constant SFR in the lower panel of Fig. 3. If the starburst is sufficiently old, let us say of age \( \tau^* \approx 50 \text{Myr} \), then there may exist evolved stars with any mass between the upper IMF limit and the critical mass \( M = 8 \text{M}_\odot \) for core-collapse supernovae. But if the burst is younger, then all stars with initial mass below a given value – \( M(\tau) \) – are still on the main sequence and only stars more massive than \( M(\tau^*) \) can explode. Different curves in the lower panel of Fig. 3 are labelled by the duration of the burst, in Myr. A Salpeter IMF is consistent with the observed \( S_{\text{Seyf}} \) if the star formation episode is younger than \( \approx 13 \text{Myr} \). This value depends only slightly on the assumed chemical composition.

5 CONCLUSIONS

We found that normal galaxies show \( S_{\text{norm}} \approx 0.27 \), a value consistent with the ratio of absolute supernova rates in SNu. With the caveat of our still-limited sample size, Seyfert galaxies show a peculiar distribution of supernova types, with higher frequency of Type Ib/c supernovae (\( S_{\text{Seyf}} \approx 1 \)) than non-active galaxies. These findings are consistent with a ‘normal’ supernova rate related to secular star formation as far as non-active galaxies are concerned. A scenario where Wolf–Rayet stars are produced by the most massive stars (\( \approx 40 \text{M}_\odot \)) and by less massive (8 \( \leq M \leq 40 \text{M}_\odot \)) primary stars of binary systems that sooner or later undergo mass transfer reproduces the observed ratio fairly well, without particular assumptions on the IMF.

A large Type Ib rate with respect to Type II supernovae, as found for Seyferts, is a new result. We consider several explanations as possible, namely a lowering of the upper mass limit for Type II precursors due to a higher metallicity, a very high binary fraction, a top-heavy IMF and a low age of the burst of star formation. While metallicity is likely to act in the observed direction, because it enhances the mass-loss rate, the amplitude of the observed effect may not be explained.

Even if the \( S \) value found for Seyfert galaxies needs confirmation with better statistics, it is interesting to note that an high \( S \) could be associated with the enhanced SFR in the circumnuclear and regions of galaxies hosting Seyfert nuclei, especially of type 2 (Dultzin-Hacyan 1995). A low age of the burst of star formation – probably triggered by interaction with a massive companion galaxy (Dultzin-Hacyan et al. 1999) – is a likely cause of the high \( S \) observed among Seyfert galaxies, as it

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requires the minor number of assumptions. This interpretation is also consistent with an evolutionary sequence leading from infrared-luminous starbursts to Seyfert 2 and eventually to Seyfert 1 galaxies, with the youngest Seyfert 1 being the ones of lowest intrinsic power and/or the ones most heavily obscured (Gu, Maiolino & Dultzin-Hacyan 2001).

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