THE ASTROPHYSICAL JOURNAL, 423:L31–L33, 1994 March 1

ON THE PROGENITORS OF TYPE Ia SUPERNOVAE IN EARLY-TYPE AND LATE-TYPE GALAXIES

MASSIMO DELLA VALLE[1] AND MARIO LIVIO[2]
Received 1993 September 27; accepted 1993 December 9

ABSTRACT

An examination of recent observational material reveals substantial differences between supernovae of Type Ia (SNs Ia) in galaxies of different Hubble types. We propose that SNs Ia in late- and early-type galaxies may have different progenitors.

A further examination of novae in galaxies of different Hubble types suggests the possibility that SNs Ia in late-type galaxies may be related to cataclysmic variable-type systems, while SNs Ia in early-type galaxies may be related to mechanisms involving an older population. About 50%–70% of the SNs Ia events in spirals observed at the La Silla and Tololo Observatories in the past 4 years appear to be located in the arms of the parent galaxy.

Subject headings: galaxies: elliptical and lenticular, cD — galaxies: spiral — nova, cataclysmic variables — supernovae: general

1. INTRODUCTION

Many of the current models for supernovae of Type Ia (SNs Ia) involve a carbon deflagration/detonation in a white dwarf (WD) driven to the Chandrasekhar limit by accretion (e.g., Nomoto, Thielemann, & Yokoi 1984; Woosley & Weaver 1986; Branch 1987; Shigeyama et al. 1992; Wheeler & Harkness 1992).

Within this general framework, there exist *single degenerate* models (e.g., Whelan & Iben 1973), in which the WD accretes mass from a nondegenerate companion (a giant or a main-sequence star) and *double degenerate* models (e.g., Iben & Tutukov 1984; Webbink 1984), which involves the merger of two WDs with a total mass exceeding the Chandrasekhar limit. *These two classes of models have generally been regarded as competing.* The main reason for this situation has probably been the fact that SNs Ia have been thought as constituting a very homogeneous class of objects, on the basis of their characteristics both at maximum light (e.g., Barbon, Ciatti, & Rosino 1973) and at late stages (e.g., Turatto et al. 1991). Therefore, a single class of progenitors seemed very reasonable.

However, recent observations suggest that significant differences between the time evolution of some spectroscopic features (in different SNs Ia) do exist (e.g., Branch, Drucker, & Jeffrey 1988; Barbon et al. 1990; Leibundgut et al. 1993). In particular, Branch & van den Bergh (1993) have shown (see also Filippenko 1989) that the blueshift of the λ6355 feature of Si II depends on the parent-galaxy type, with the lowest expansion velocities occurring in early-type galaxies. These observations strongly suggest that the physical characteristics of SNs Ia may be different in early- and late-type galaxies.

Furthermore, there exists some (weaker) evidence that SNs Ia in late-type galaxies are brighter (by ∼1 mag) than those in early-type (van den Bergh & Pazder 1992). However, different values of $(B-V)^0_{\max}$ than the one used by the latter authors (e.g., Della Valle & Panagia 1992; Cappaccioli et al. 1990) may reduce this difference to ∼0.3 mag (see also van den Bergh & Pierce 1992). Nevertheless, Phillips (1993) and Suntzeff (1994) find a significant dispersion in the absolute magnitudes at maximum light of SNs Ia and conclude that these differences suggest either a range in progenitor masses or variations in the explosion mechanism.

Finally, the existence of peculiar objects like the underluminous supernovae 1991bg (Filippenko et al 1992; Leibundgut et al. 1993) and the overluminous 1991T (Phillips et al. 1992; Ruiz-Lapuente et al. 1992; Filippenko et al. 1992), could be regarded as representing extreme cases of the intrinsic differences between SNs Ia occurring in ellipticals and spirals, respectively. It nonetheless remains true that SNs Ia appear to form a spectroscopic sequence, with the majority being "spectroscopically normal" (Branch, Fisher, & Nugent 1993).

In this *Letter* we examine further the possibility that intrinsic physical differences exist between SNs Ia occurring in early- and late-type galaxies, and we suggest that they may have different progenitors.

2. OTHER DIFFERENCES BETWEEN SNs Ia IN GALAXIES OF DIFFERENT HUBBLE TYPES

The fact that SNs Ia are the only ones to occur in ellipticals has sometimes been taken to mean that *all* SNs Ia have to be associated with very old populations. As noted already in the Introduction (and see below), the differences between SNs Ia in early- and late-type galaxies bring this conclusion into question.

Van den Bergh (1990) cross-correlated the Asiago Supernova Catalogue (Barbon, Cappellaro, & Turatto 1989) with the Shapley-Ames Catalogue and was able to show that the frequency of SNs Ia (per unit of H luminosity) is an order of magnitude higher in late-type spirals than it is in ellipticals, lenticulars, and early-type spirals. This important result was obtained under the general assumption that all Shapley-Ames galaxies are equally monitored. Possible caveats to such an approach are related to the possibility that the numerous selection effects on the discovery of SNs are neglected (e.g., Cappellaro et al. 1993a). A suitable route to avoid this danger is provided by the SN rates derived by applying the *control time* methodology (e.g., Cappellaro et al. 1993b). After combining

[1] La Silla Observatory, European Southern Observatory, Alonso de Cordova 3107, Vitacura, Casilla 19001, Santiago, Chile. Also Dipartimento di Astronomia, Universita di Padova.

[2] Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218. Also Department of Physics, Technion, Haifa.

the SN rate per unit of B luminosity of the parent galaxy, provided by the latter authors, with the average $(B-K)$ colors derived from the spectral energy distribution of each galaxy type (Yoshii & Takahara 1988; see also Table 2 in § 3), we confirm that the SN frequency per unit of K luminosity in late-type galaxies is at least a factor ≈ 5–10 larger than it is in early-type galaxies.

The "site" of the SN explosions is also very suggestive. A close inspection of the "best seeing frames" of the SNs Ia observed at the La Silla and Tololo Observatories in the past 4 years reveals that a significant fraction of the events in spirals appear to be located in the arms of the parent galaxy. From a total sample of 24 entries (Table 1), we could extract a fiducial sample of 16 well-imaged face-on (or $i \leq 30°$) galaxies. In at least 11 cases, the SNs were clearly superposed on the arms of the parent galaxies at distances from the center of 5–30 kpc (for $H_0 = 50$ km s^{-1} Mpc^{-1}), with the only exception being 1993T (60 kpc). For the remaining eight SNs, mostly occurring in anonymous distant galaxies ($z \approx 0.03$), the quality of the data is not sufficient to provide useful hints on the location of the SN inside the parent galaxy. The previous figures enable us to set a lower limit at ≈ 0.5 on the fraction of SNs Ia which appear superposed on the arms of the parent galaxy. When considering only the galaxies belonging to the fiducial sample this figure increases to ≈ 0.7. This suggests that the SNs Ia in spirals may be associated (in a statistical sense) with a younger population of progenitors (more massive) than those in ellipticals. We note that our results are not at variance with the conclusions by van Dyk (1992), who on the basis of his data could not exclude the association of SNs Ia with an intermediate age stellar population (age $\geq$ a few times 10^7 yr).

For at least two galaxies that exhibited in the last century multiple type Ia events—NGC 5253 (van den Bergh & Tammann 1991) and NGC 4753 (Branch & van den Bergh 1993)—the authors hypothesized that the observed enhanced rate of SNs Ia may be the consequence of episodes of star formation in the relatively recent past (0.5–1) $\times 10^9$ years ago). Similar arguments may be applied to the recent case of MCG + 10-24-007 (Gomez & Lopez 1993).

The possibility that the rate of SNs Ia can be increased by recent phases of star formation is also supported by the high SN Ia rate in I0-type galaxies (van den Bergh 1990). Again, SNs Ia induced by recent starburst episodes could be associated (on the average) with younger, more massive progenitors than those in ellipticals and lenticulars (which are associated with very old stellar populations).

The evidence presented in §§ 1 and 2 suggests that at least a considerable fraction of the SNs Ia in late-type spirals may be linked to an evolved population of the young disk, rather than to the very old population found in ellipticals and bulges.

TABLE 1

The Site of Recent SNs Ia in Spiral Galaxies

SN	Site	SN	Site
1990T	Arm	1992ag	Bulge
1990ab	Arm	1992ae	Arm
1991M	?	1992al	Arm
1991S	Arm	1992bc	Arm
1991T	Arm	1992bg	?
1991U	Bulge?	1992bh	Bulge
1991X	Bar	1992bs	?
1991ag	?	1993B	Arm?
1991bj	Arm	1993H	Bar
1992K	?	1993L	Arm
1992E	Arm	1993Q	Arm
1992P	?	1993T	Halo

3. A CATACLYSMIC VARIABLES–SNa Ia CONNECTION?

In a recent paper Della Valle et al. (1993, hereafter DBRL) have shown that the nova rate per unit of K (and H) luminosity in late-type galaxies is higher (by a factor 3–4) than that in early-type galaxies. In Table 2 we compare the rates of novae for the sample of (individual) galaxies studied by DBRL with the rates of SNs Ia for the same (morphological type) galaxies. In the third column we give the SNs Ia rate per 100 years, per unit of B luminosity (taken from Cappellaro et al. 1993b); in the fourth column the same, for K luminosity. In the fifth column we give the nova rate (per 100 years, per unit of K luminosity), taken from DRBL, and in the sixth, the ratio between the nova and supernova rates. We assume that K luminosity is a good tracer for the evolved stellar population (see, however, caveats by Wheeler 1992; in our case, a possible contamination by bright young stars in late-type galaxies should affect both the nova and supernova rates).

Columns (4) and (5) of Table 2 demonstrate that both the nova and SNs Ia rates are considerably higher in late-type galaxies.

Interestingly enough, one can attempt, following the van den Bergh (1988) prescription, to use the ratio of the rates r_N/r_{SN} to estimate the Galactic SN Ia rate. Taking the galaxy to be of type Sb, and with a value of the Galactic nova rate of ~ 20 novae/yr (Della Valle & Livio 1993), we obtain from Table 2 one SN Ia per $\sim 5700/20 = 285$ yr; that is, 3.5×10^{-3} SNs Ia per year, which agrees reasonably well with the estimate of about 3×10^{-3} yr^{-1} (Cappellaro et al. 1993b; van den Bergh & Tammann 1991).

The data in Table 2, when considered in conjunction with the data on the different explosion strengths (presented in § 1), raise the following two important questions: (1) Is it possible that the majority of progenitors of SNs Ia in late-type galaxies are different from those in early-types? and (2) Is there any connection between the SNs Ia and novae (or cataclysmic variable-type systems in general)?

Before we attempt to answer these questions, the following should be noted: Livio & Truran (1992) and Livio (1993) examined the question of whether cataclysmic variables (CVs) in our Galaxy could be responsible for SNs Ia, by increasing the WD to the Chandrasekhar mass (see also Wheeler 1992). Their conclusion was that while the WDs in certain subclasses of CVs (e.g., the recurrent novae and systems that experience steady burning; see Livio 1993 for details) are able to reach the Chandrasekhar limit, the total rate of these events in our Galaxy is too low ($\sim 10^{-4}$ yr^{-1}) to explain the estimated SNs Ia rate.

However, DBRL have shown that the overproduction of

TABLE 2

Frequency of SNs Ia and Novae in Galaxies of Different Hubble Types

Galaxy (1)	Type (2)	r_{SN}/L_B (3)	r_{SN}/L_K (4)	r_N/L_K (5)	r_N/r_{SN} (6)
Virgo	E	0.11	0.01	2.1×10^2	2×10^4
N5128	S0	0.15	0.04	1.7×10^2	4.3×10^3
M31	Sab-Sb	0.12	0.03	1.7×10^2	5.7×10^3
M33	Scd	0.48	0.16	3.3×10^2	2.1×10^3
LMC	Sm	0.20	0.14	6.2×10^2	4.4×10^3

novae in late-type galaxies could be a consequence of the fact that *novae in these galaxies are mostly associated with massive WDs* ($M_{WD} \sim 1.2$–$1.4\ M_{\odot}$), while the novae in early-type and bulge-dominated galaxies are typically associated with WD masses of $M_{WD} \sim 0.7$–$0.9\ M_{\odot}$. This association, in turn, probably reflects the younger population of late-type galaxies.

Since it is much easier to grow massive WDs in CV systems to the Chandrasekhar mass (e.g., Livio 1993; Livio & Truran 1992), it is perhaps possible that a considerably larger fraction of these systems in late-type galaxies could reach the critical mass.

It is therefore tempting to make the following speculative suggestion: The main class of progenitors of SNs Ia in late-type galaxies is different from that in early-types. The progenitors in early-types may be double degenerate systems (see, e.g., Yungelson et al. 1994 for the most recent evaluation of the status of some aspects of this scenario), or WDs that explode before reaching the Chandrasekhar limit (e.g., Iben & Tutukov 1991; Livne & Glasner 1991; Limongi & Tornambe 1991; Fujimoto & Taam 1982; Ruiz-Lapuente et al. 1993; and in particular Woosley & Weaver 1994), as in symbiotic systems (Kenyon et al. 1993; Munari & Renzini 1992). However, the progenitors in late-type galaxies may be CV-type systems, in which massive WDs accrete at a high rate. Such systems include recurrent novae (e.g., Starrfield, Sparks, & Truran 1985; Livio 1993) and may include systems that undergo steady burning (of the type of CAL83 and CAL87, see, e.g., van den Heuvel et al. 1992 and references therein).

A potential difficulty with the suggestion of CV-type systems as progenitors is the fact that some calculations show that massive WDs accreting at a high rate will preferentially produce accretion-induced collapses (AICs) rather than SNs Ia (e.g., Nomoto & Kondo 1991). However, we feel that the uncertainties involved in this type of calculations are still quite large (see, e.g., Canal, Isern, & Labay 1990 and references therein).

Clearly the ultimate test for the proposed scenario should be provided by searches for hydrogen in SNs Ia using high signal-to-noise data. Early estimates (e.g., Applegate & Terman 1989 and references therein) concluded that a hydrogen mass fraction of $X(\mathrm{H}) \gtrsim 0.01$ should exist in cataclysmic variable-type systems, from material ablated from the secondary. Hydrodynamic calculations by Livne, Tuchman, & Wheeler (1991, 1992) indicated, however, that the hydrogen is lagging behind, in the inner, low-velocity ejecta (rather than being in the outer, fast-moving ejecta). This is a consequence of the blast wave wrapping around the companion star (an earlier suggestion to this effect was made by Chugai 1986). Therefore, the hydrogen emission will have to be distinguished from the dominating (at late stages) [Fe II] emission.

4. CONCLUSIONS

On the basis of recent observations that suggest that substantial differences exist between SNs Ia in early- and late-type galaxies, we suggest that SNs Ia in late-type spirals may have different progenitors than those in ellipticals. A comparison with novae in galaxies of different Hubble types leads us to suggest the possibility that the progenitors of SNs Ia in late-type galaxies are CV-type systems, while the more conventional scenarios (e.g., double degenerates) operate in early-types.

We are indebted to Mark Phillips and Mario Hamuy for giving us access to the archive of the Tololo's supernova search.

REFERENCES

Applegate, J. H., & Terman, J. L. 1989, ApJ, 340, 380
Barbon, R., Benetti, S., Cappellaro, E., Rosino, L., & Turatto, M. 1990, A&A, 237, 79
Barbon, R., Cappellaro, E., & Turatto, M. 1989, A&AS, 81, 421
Barbon, R., Ciatti, F., & Rosino, L. 1973, A&A, 25, 241
Branch, D. 1987, in Encyclopedia of Physical Science and Technology, vol. 13 (New York: Academic), 507
Branch, D., Drucker, W., & Jeffrey, D. J. 1988, ApJ, 330, L117
Branch, D., Fisher, A., & Nugent, P. 1993, AJ, in press
Branch, D., & van den Bergh, S. 1993, AJ, 105, 2231
Canal, R., Isern, J., & Laboy, J. 1990, ARA&A, 28, 183
Cappaccioli, M., Cappellaro, E., Della Valle, M., D'Onofrio, M., Rosino, L., & Turatto, M. 1990, ApJ, 350, 110
Cappellaro, E., Turatto, M., Benetti, S., Tsvetkov, D., Bartunov, O., & Makarova, I. 1993a, A&A, 268, 472
———. 1993b, A&A, 273, 383
Chugai, N. N. 1986, Soviet Astron., 30, 563
Della Valle, M., Bianchini, A., Rosino, L., & Livio, M. 1993, A&A, submitted (DBRL).
Della Valle, M., & Livio, M. 1993, A&A, in press
Della Valle, M., & Panagia, N. 1992, AJ, 104, 696
Filippenko, A. V. 1989, PASP, 101, 588
Filippenko, A. V., et al. 1992a, AJ, 104, 1543
———. 1992b, ApJ, 384, L15
Fujimoto, M. Y., & Taam, R. E. 1982, ApJ, 260, 249
Gomez, G., & Lopez, R. 1993, AJ, 106, 245
Iben, I., Jr., & Tutukov, A. V. 1984, ApJS, 54, 335
———. 1991, ApJ, 370, 615
Kenyon, S. J., Livio, M., Mikolajewska, J., & Tout, C. A. 1993, ApJ, 407, L81
Leibundgut, B., et al. 1993, AJ, 105, 301
Limongi, M., & Tornambe, A. 1991, ApJ, 371 317
Livio, M. 1993, in Cataclysmic Variables and Related Physics, ed. O. Regev & G. Shaviv, Ann. Israeli Phys. Soc., in press
Livio, M., & Truran, J. W. 1992, ApJ, 389, 695
Livne, E., & Glasner, A. S. 1991, ApJ, 370, 272
Munari, U., & Renzini, A. 1992, ApJ, 397, L87
Nomoto, K., & Kondo, Y. 1991, ApJ, 367, L19
Nomoto, K., Thielemann, F.-K., & Yokoi, K. 1984, ApJ, 286, 644
Phillips, M. M. 1993, ApJ, 413, L105
Phillips, M. M., Wells, L., Suntzeff, N., Hamuy, M., Leibundgut, B., Kirshner, B., & Foltz, C. 1992, AJ, 103, 1632
Ruiz-Lapuente, P., Cappellaro, E., Turatto, M., Gouiffes, C., Danziger, J., Della Valle, M., & Lucy, L. 1992, ApJ, 387, L33
Ruiz-Lapuente, P., et al. 1993, Nature, 365, 728
Shigeyama, T., Nomoto, K., Yamaoka, H., & Thielemann, F.-K. 1992, ApJ, 386, L13
Starrfield, S. G., Sparks, W. M., & Truran, J. W. 1985, ApJ, 291, 136
Suntzeff, N. B. 1994, in IAU Colloq. 154, Supernovae and Supernova Remnants, ed. R. McCray, in press
Turatto, M., Cappellaro, E., Barbon, R., Della Valle, M., Ortolani, S., & Rosino, L. 1990, AJ, 100, 771
van den Bergh, S. 1988, Comm. Astrophys., 12, 131
———. 1990, PASP, 102, 1318
van den Bergh, S., & Pazder, J. 1992, ApJ, 390, 34
van den Bergh, S., & Pierce, M. 1992, PASP, 104, 408
van den Bergh, S., & Tammann, G. 1991, ARA&A, 29, 363
van den Heuvel, E. P. J., Bhattacharya, D., Nomoto, K., & Rappaport, S. A. 1992, A&A, 262, 97
van Dyk, S. D. 1992, AJ, 103, 1788
Webbink, R. F. 1984, ApJ, 277, 255
Wheeler, J. C. 1992, in IAU Symp. 151 Evolutionary Processes in Interacting Binary Stars, ed. Y. Kondo, R. F. Sistero, & R. S. Polidan (Dordrecht: Kluwer), 225
Wheeler, J. C., & Harkness, R. P. 1992, Rep. Prog. Phys., 53, 1467
Whelan, J., & Iben, I., Jr. 1973, ApJ, 186, 1007
Woosley, S. E., & Weaver, T. A. 1986, ARA&A, 24, 205
———. 1994, ApJ, in press
Yoshii, Y., & Takahara, F. 1988, ApJ, 326, 1
Yungelson, L., Livio, M., Tutukov, A., & Saffer, R. 1994, ApJ, 420, 336