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ON THE FREQUENCY OF OCCURRENCE OF RECURRENT NOVAE AND THEIR ROLE AS TYPE Ia SUPERNOVA PROGENITORS

MASSIMO DELLA VALLE[1,2] AND MARIO LIVIO[2]

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ABSTRACT

We have determined the frequency of occurrence of recurrent novae (RNe) for the Galaxy, M31, and the LMC. We find that the ratio between the rate of outbursts of recurrent and classical novae (CNe) is in the range $n_{\rm out}$(RNe)/$n_{\rm out}$(CNe) ~ 0.1–0.3. The implications of this result for the realization frequency of RNe as potential progenitors of Type Ia supernovae are also discussed. RNe are not the major class of progenitors of Type Ia supernovae.

Subject headings: galaxies: individual (M31) — Magellanic Clouds — novae, cataclysmic variables — stars: statistics — supernovae: general

1. INTRODUCTION

The merger of CO + CO white dwarfs or the accretion of hydrogen onto a white dwarf via Roche lobe overflow, from a subgiant donor, are currently believed to be the most promising candidates for the progenitors of Type Ia supernovae (SNe Ia) (e.g., Branch et al. 1995; Livio 1996). Cataclysmic variable-type systems may in particular represent a channel to SNe Ia in the relatively younger stellar population of late type galaxies (e.g., Della Valle & Livio 1994a).

Among the cataclysmic variable (CV)-type systems, two classes of objects look particularly attractive: the recurrent novae and the supersoft X-ray sources. Livio & Truran (1994) suggested, on the basis of the abundance determinations of the ejecta of recurrent novae (RNe), that the mass of the envelope ejected during the outburst might be smaller than the amount of the accreted material, thus making RNe (or at least the more massive objects of this population) promising candidates to growth in the mass of the white dwarf (WD) toward the Chandrasekhar limit. Such an evolution could drive the system to an SNe Ia explosion. The same authors pointed out that the outbursts of RNe like U Sco (Webbink et al. 1987), T Pyx (and perhaps V394 Cra and N LMC 1990 number 2 [see also Livio 1993]), could be explained in terms of thermonuclear runaways (TNRs) on the surface of the WD only if these systems satisfy the following conditions: $M_{\rm WD} \gtrsim 1.25\ M_\odot$, and $\dot{M} \gtrsim 10^{-8}\ M_\odot\ {\rm yr}^{-1}$. This general conclusion has been recently confirmed by the detailed calculations of Prialnik & Kovetz (1995). These authors show that accretion at rates of $\dot{M} \gtrsim 10^{-7}\ M_\odot\ {\rm yr}^{-1}$ onto a massive WD ($\gtrsim 1.25\ M_\odot$) results in an increase in the mass of the WD and implies a recurrence time between two consecutive outbursts shorter than 50 yr which is quite typical for Galactic RNe (see Fig. 1). The same authors also show that for $\dot{M} \lesssim 10^{-8}$ the mass of the WDs in CVs tends to decrease with time, dismissing these objects as potential progenitors of SNe Ia. At $\dot{M} = 10^{-8}\ M_\odot\ {\rm yr}^{-1}$, the ultimate fate of the WD is determined by its temperature, with the possibility of increasing in mass for relatively low mass ($M_{\rm WD} \lesssim 1\ M_\odot$) and hot ($T_{\rm WD} \gtrsim 3 \times 10^7$) WDs. Since the accretion rates in classical novae are usually in range $10^{-11} \lesssim M_\odot \lesssim 10^{-8}$, this excludes the main bulk of classical novae (CNe) systems from being SNe Ia progenitors.

Indeed, population synthesis calculations (e.g., Yungelson et al. 1995, 1996) give a rate of SNe Ia obtained from CV-type progenitors (rather the rate at which the Chandrasekhar mass is reached) of $v_{\rm SNeIa} \sim$ (a few) $\times\ 10^{-5}\ {\rm yr}^{-1}$ in young stellar populations and an even smaller rate in old ones.

The goal of the present paper is to attempt to evaluate on *empirical grounds* the realization frequency for this class of potential progenitors of SNe Ia. We intend to use global rates of novae determined in several surveys (which do not distinguish between CNe and RNe). Consequently, we will determine the ratio of RNe to CNe and use that to determine the rate of RNe.

2. RNe IN THE MILKY WAY

Figure 2*a* shows the trend of the number of nova discoveries during the last century. Using Duerbeck's compilation (1987) for novae that occurred before 1986 and the data provided by the IAU circulars for novae until 1996, we found that 252 CNe and nine RNe have been discovered so far (see Table 1). Following Sekiguchi (1992), we have also included among the RNe AS Psc and V1017 Sgr, although in both cases no spectroscopic confirmations are available and in the latter case only the outburst of 1919 might have been powered by a TNR (see Webbink et al. 1987). Since all novae are, in principle, recurrent, we should make it clear that when we talk about recurrent novae, we adopt the definition of Webbink et al. (1987), and we refer in general to systems which have recurrence times of less than ~100 yr.

The nine recurrent novae (dark histogram in Fig. 2*a*) have produced 29 nova outbursts which gives a ratio of number of outbursts of $n_{\rm out}$(RNe)/$n_{\rm out}$(CNe) ≈ 0.12. However, there exist some indications that this number could be larger. For example, it should be noted that the number of galactic RNe has doubled in the last 15 yr, whereas the number of CNe has increased, during the same period of time, by only about 20%. This difference could be due to the increase in the number of nova discoveries in the 1930–1940s (see Fig. 2*a*) combined with the fact that the typical recurrence times of the outbursts of RNe are shorter than 60 yr (see Fig. 1). The previous outbursts of the four most recent galactic RNe were indeed recorded after 1930; thus it is possible that a nonnegligible fraction of the RNe, the first outbursts of which were missed before 1930, are

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[1] Dipartmento di Astronomia, Universita de Padova, Italy.

[2] Space Telescope Institute, 3700 San Martin Drive, Baltimore, MD 21218.

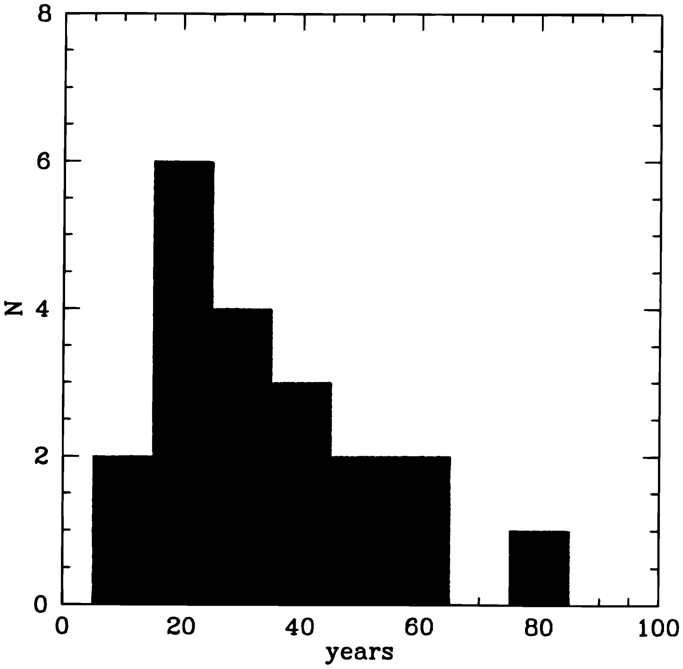

FIG. 1.—The frequency distribution of recurrence times between outbursts for Galactic recurrent novae.

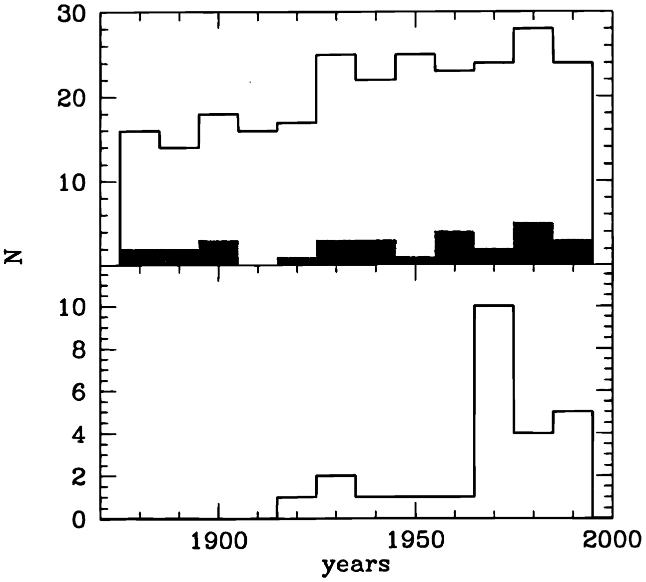

FIG. 2.—*Top panel*: The rate of discovery of Galactic novae in the last 120 yr. The dark histogram represents the rate of discovery of recurrent novae. *Bottom panel*: The rate of discovery of novae in the LMC.

TABLE 1

RNe IN THE MILKY WAY

Name	Year of Outbursts
U Sco..........	1863, 1906, 1936, 1979, 1987
T CrB	1866, 1946
T Pyx..........	1890, 1902, 1920, 1944, 1966
RS Oph	1898, 1933, 1958, 1967, 1985
V1017 Sgr......	1901, 1919, 1973, 1991
V745 Sco	1937, 1989
V394 CrA	1949, 1987
V3890 Sag......	1962, 1990
AS Psc..........	1963, 1980

currently classified as CNe. By limiting the statistics, for example, to the last 15 yr we find that the ratio $n_{\rm out}$(RNe)/$n_{\rm out}$(CNe) becomes $\gtrsim 0.15$. This last figure still does not take into account one other observational bias which could increase this ratio. The light curves of RNe are often characterized by a very fast early decline (e.g, N LMC 1990 number 2; U Sco). This fact acts against the discovery of the outbursts of RNe, particularly in external galaxies.

3. THE RNe IN THE LMC

It is difficult to estimate the rate of RNe in the LMC due to the scanty statistics that are currently available. From 1926, 25 nova outbursts have been recorded and only two of them, N LMC 1968 = N LMC 1990 number 2, have been found to be produced by the same object (Sekiguchi 1992). However, an inspection of Figure 2*b*, in which we present the number of nova discoveries in the LMC, shows that the monitoring of the LMC for nova searches has been very discontinuous in the past, with an average of one discovery per decade until the 1970s. This rate has considerably increased during the last 28 yr, during which most of the nova outbursts (20) in the LMC have been discovered. Taking the above figures at face value we find that $n_{\rm out}$(RNe)/$n_{\rm out}$(CNe) $\approx 2/18 = 0.11$. However, this figure should definitely be regarded as a lower limit. By assuming a nova rate greater than about two novae per year (Graham 1979; Capaccioli et al. 1989), we estimate that about 64% of the nova outbursts during the last 28 yr have been missed due to infrequent monitoring. Since the discovery of a recurrent nova consists of observing at least two outbursts during a given interval of time Δt, we can estimate, as the correction to be applied to the number of RNe discovered in the LMC, the factor $\sim 0.36^{-2}$. With this correction applied, the ratio $n_{\rm out}$(RNe)/$n_{\rm out}$(CNe) can increase up to 0.33. On the other hand, if a RN undergoes more than two outbursts during the same interval Δt, then its probability of discovery becomes

$$\sum_{r=2}^{n} \frac{n!}{r!(n-r!)!}(p)0.64^{(n-r)},$$

where n is the number of outbursts that occurred in Δt and r is the number of detected outbursts (at least 2). In Figure 1 we have shown the frequency distribution of the recurrence times (between two consecutive outbursts) for Galactic novae. The distribution is skewed, with a long tail extending up to 80 yr, and an average recurrence time of ≈ 30 yr. We note that recurrence times shorter than 30 yr, which could produce more than two outbursts during the interval of time spanned by the observations of the LMC (28 yr), represent $\lesssim 15\%$ of the entire sample. Taking this into consideration, we obtain that the ratio $n_{\rm out}$(RNe)/$n_{\rm out}$(CNe) might be slightly smaller than quoted above, of the order of $\gtrsim 0.25$. This last result is based on the assumption that the distributions of the recurrence times in the LMC and in the Galaxy are similar.

4. RNe IN M31

In the present study we have used 321 novae coming from the main surveys carried out on M31 for nova searches. These include Hubble (1929; =H), Arp (1956; =A), Rosino (1964, 1973; =R), Rosino et al. (1989; =R), Ciardullo et al. (1987; =C), Sharov & Alksnis (1991; =SA), and Tomaney & Shafter (1992; =TS), Other contributions like those of: Duncan (1928), Baade and Swope (1963, 1965) have not

TABLE 2

Coordinates of 16 Novae in M31 Zero Points of the Frames

Name (1)	Name (2)	X_1 (3)	Y_1 (4)	X_2 (5)	Y_2 (6)	ΔX (7)	ΔY (8)
R80	SA1	−2.2	5.0	−2.247	5.031	0.05	−0.03
R85	SA6	−2.8	−0.4	−2.5	−0.4	−0.3	0.0
R87	SA8	15.0	5.0	14.86	5.24	0.14	−0.24
R94	SA12	−7.56	0.08	−7.604	0.10	0.04	−0.02
R140......	SA20	4.96	3.02	5.101	3.148	−0.14	0.13
R111......	C6	3.80	2.76	3.916	2.736	−0.12	0.02
R128......	C4	3.27	−0.68	3.157	−0.724	0.11	0.04
R130......	C5	1.81	−2.44	1.881	−2.573	−0.07	0.13
R131......	C3	8.21	−2.99	8.284	−3.014	−0.07	0.02
R134......	C8	−3.87	2.63	−3.83	2.597	−0.04	0.03
R138......	C18	1.09	−0.35	1.058	−0.4334	0.03	0.08
R140......	C26	4.96	3.02	5.073	3.107	−0.11	−0.09
R142......	C29	5.38	2.89	5.498	2.947	−0.12	−0.06
C13	SA17	2.393	−2.458	2.426	−2.411	−0.03	−0.05
C26	SA20	5.073	3.107	5.101	3.148	−0.03	−0.04
C32	TS1	−4.066	−2.524	−4.026	−2.471	−0.04	−0.05

been used either because the coordinates of the novae were not provided or because they were concerned with the search of novae in the halo of M31 (Meinunger 1973), whereas the nova surveys have been mainly concentrated on the bulge and the spiral arms. These surveys cover, rather sparsely, an interval of time of about 60 yr, which is about twice the average recurrence time for Galactic RNe, and therefore, we should expect (at least in principle) to detect some RN events in these surveys.

All the novae have been referred to the standard system of normal axes X and Y: centered at $\alpha_{1950} = 00^{\rm h}40^{\rm m}00^{\rm s}$ and $\delta_{1950} = 40°59'42''.9$ with a position angle of the positive X axis of P.A. = 38°, the same as the apparent major axis of the disk of M31 (see Walterbos 1986). This system was first introduced by Arp (1956) and afterward used by Rosino (1964, 1973) and Rosino et al. (1989). In his original paper, Hubble (1929) used a similar reference frame with same origin of the axes and opposite signs. In order to reduce the coordinates of the novae coming from Ciardullo's (1987), Sharov & Alksnis's (1991), and Tomaney & Schafter's (1992) compilations to the standard reference frame, we have derived the following transformation for small $\Delta\alpha$ and $\Delta\beta$:

$$x = Y/\cos\theta + (X - Y \times \tan\theta)\sin\theta$$

and

$$y = (X - Y \times \tan\theta)\cos\theta$$

with $X = \Delta\alpha\cos\delta$ and $Y = \Delta\delta$, and $\theta = 38°$.

In the next step, we have cross-correlated the coordinates of each nova with those of the other 320, in order to search for coincidences within an appropriate error box. The size of the error box has been derived by studying the differences in the coordinates of 16 objects which have been discovered independently by different observers. In Table 2, we give in the first two columns the identification of the nova according to the different sources, in columns (3), (4), (5), (6) the coordinates of each object as measured in the original reference frame, or after having transformed the original α and δ coordinates to X and Y, and in columns (7) and (8) we give the respective differences (all of these figures have been expressed in arcminutes).

From the data of the last two columns of Table 2 we have derived: $\sigma_x = 0'.12$ and $\sigma_y = 0'.10$. In the following, we have considered as potential RNe only the objects whose coordinates satisfy the conditions: $(x_i = x_i') \leq 0'.12$ and $(y_i - y_i') \leq 0'.10$. A comparison with the data of Table 2 shows that by adopting for the size of the error box the 1 σ criterion would have resulted in the loss of only two objects out of 16 (∼10%).

The results of our analysis were complemented by a visual inspection (marked in Table 3 with asterisk) of the plates and/or maps for Rosino's and Ciardullo's surveys. In Table 3, columns (1) and (2) give the nova identification, columns (3), (4), (5), and (6) report the coordinates of the objects, and column (7) gives the interval of time between the outbursts. We find besides the two RNe already found by Rosino (1973), R48 = R79, and R66 = R81, five new candidates. Particularly interesting is the case of R7 = R29 = R40 = H31 having three outbursts visually confirmed. However, we should note that four more cases belonging to Rosino's and Ciardullo's samples passed our selection criteria and they were discarded after the visual inspection of the maps and/or plates. This may indicate that about one-half of the events reported in Table 3 and not confirmed by visual inspections of the plates represent only coincidences.

In order to make a quantitative comparison between the frequency distributions of the recurrence times of the outbursts for M31 and Galactic RNe, we have performed a K-S test on the two populations. Our analysis (admittedly obtained on scanty statistics), does not point out, at a confidence level of 95%, the existence of two different frequency distributions.

To determine the ratio between RN and CN outbursts,

TABLE 3

RNe in M31

Name (1)	Name (2)	X_1 (3)	Y_1 (4)	X_2 (5)	Y_2 (6)	ΔT (7)
R7	R40	0.1	2.9	0.1	2.8	6*
R29	R40	0.0	2.9	0.1	2.8	2*
R40	H31	0.1	2.8	0.0	2.7	38
R48	R79	−4.7	7.0	−4.7	7.1	5*
R66	R81	−11.0	−11.4	−11.0	−11.4	2*
H7	H79	−1.5	−1.95	−1.5	−2.0	10
R132......	A10	−3.58	5.72	−3.7	5.7	28
R17	H53	2.9	−0.1	2.8	−0.2	32
R119......	H51	−10.16	0.60	−10.2	0.5	57

we need first to account for the 16 objects which belong to different samples and second, for the 18 outbursts due to seven RNe. Therefore, the number of potential CN outbursts decreases to 287 and the ratio $n_{\rm out}$(RNe)/$n_{\rm out}$(CNe) turns out to be ≈ 0.07. Both figures should be corrected for incompleteness of the surveys. Capaccioli et al. (1989) have shown that the *actual* number of nova outbursts occurring in M31 is likely to be increased by about $\frac{1}{3}$ with respect to the *observed* one. Therefore, we derive a corrective factor, to be applied to the number of RNe, of $\sim(\frac{2}{3})^{-2}$. With these figures we obtain that the ratio $n_{\rm out}$(RNe)/$n_{\rm out}$(CNe) is ≈ 0.11. Since the time spanned by the surveys is as long as twice the typical recurrence time between two consecutive outbursts, it is very likely that most of the RN population of M31 has exhibited during this time more than two outbursts. If this is the case, the previous correction has overestimated the actual correction factor and therefore, the obtained ratio should be regarded as an upper limit.

In the following we shall assume for M31 $n_{\rm out}$(RNe)/$n_{\rm out}$(CNe) ~ 0.1.

5. DISCUSSION

We have determined the frequency of outbursts of RNe for M31, the LMC, and the Galaxy. For M31, this study has been mostly carried out on the basis of an original research based on photographic archive material of the Asiago Observatory. For the LMC and the Galaxy the frequencies of occurrence of RNe have been derived by a critical review of the data sets available in the literature. We have found that the ratios between the rates of outbursts of RNe and CNe for the Milky Way, LMC, and M31 are likely to be in the range $0.1 \lesssim n_{\rm out}({\rm RNe})/n_{\rm out}({\rm CNe}) \lesssim 0.3$.

After assuming a nova rate of 29 novae yr^{-1} for M31 (Capaccioli et al. 1989), $\gtrsim$two novae yr^{-1} for the LMC (Graham 1979; Capaccioli et al. 1990), and 24 novae yr^{-1} for the Galaxy (Della Valle & Livio 1994b), we find a rate of recurrent nova outbursts of $R_{\rm RNe} = 2.9$ RNe yr^{-1} for M31, three RNe yr^{-1} for the Galaxy, and 0.5 RNe yr^{-1} for the LMC.

These RN rates are currently supported by a population of progenitors $N = \Delta T_{\rm rec} R_{\rm RNe}$, where $\Delta T_{\rm rec}$ is the mean recurrence time. Taking $\Delta T_{\rm rec} = 30$ yr (see § 3), we find $N = 87$, 90, and 15 for M31, the Galaxy, and the LMC, respectively.

We can now ask the question, at what rate can the accreting WDs in these systems reach the Chandrasekhar mass. The accretion rate that is required in order to produce the observed recurrence times is of order 10^{-7} $M_\odot$ yr^{-1} (Prialnik & Kovetz 1995). The accretion of $\sim$0.1–0.2 $M_\odot$ will therefore require $\sim$(1–2) $\times$ 10^6 yr. Using the numbers obtained above, we therefore obtain a birth rate of (4.4–8.7) $\times$ 10^{-5} yr^{-1}, (4.5–9) $\times$ 10^{-5} yr^{-1}, and (0.75–1.5) $\times$ 10^{-5} yr^{-1} for M31, the Galaxy, and the LMC, respectively. These numbers should definitely be regarded as upper limits, since they assume that all the WDs in these systems will reach Chandrasekhar mass (ignoring, for example, helium shell flashes). Interestingly, the upper limit on the rate obtained for the Galaxy *agrees extremely well with the results of population synthesis calculations* (Yungelson et al. 1995, 1996; Livio 1993). This gives observational support to this type of calculations, which necessarily involve many assumptions.

Given the fact that the deduced SNe Ia rates are 8.5×10^{-3} yr^{-1}, $\sim 3 \times 10^{-3}$ yr^{-1}, and 5×10^{-4} yr^{-1} for M31, the Galaxy, and the LMC, respectively (e.g., Cappellaro et al. 1993; van den Bergh & Tammann 1991), we find that RN-type systems can account for at most a few percent of the SNe Ia rates.

Two more points should be made. (i) The nova rates in external galaxies may have been underestimated, due to the thickness of the dusty disks (e.g., Warner 1995). We can estimate the order of magnitude of this effect by comparing the Galactic nova rate determined by Liller & Mayer (1987) (which was obtained without scaling from the nova rates of the galaxies in the Local Group) to that of Della Valle & Livio (1994a; which did use such a scaling). The ratio turns out to be 73/24 $\sim$ 3. While this will not change the ratio $n_{\rm out}$(RNe)/$n_{\rm out}$(CNe), it will increase the absolute rates of RN outbursts (still not sufficiently to account for the SNe Ia rates though). (ii) Our discussion does not in itself affect the possibility that *permanent* supersoft X-ray sources are the progenitors of SNe Ia, since these sources burn hydrogen steadily (e.g., van den Heuvel et al. 1992) and thus, do not enter the outburst statistics described in this paper.

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