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The space density of classical novae in the galactic disk

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Abstract. A new determination of the space density of classical novae is presented. Comparison of the properties of nova populations in M31, the Galaxy and the LMC, permits to set the outburst rate of novae belonging to the disk of the Galaxy to 5±2.5 novae per year and their outburst density to $\rho_{\rm out} = \rho_{\rm CN}/T_{\rm R} = 0.30\,(\pm 0.15) \times 10^{-10}$ pc^{-3} yr^{-1}. The frequency distribution of absolute magnitudes at minimum of 24 fast galactic novae suggests an accretion of $\langle \dot{M} \rangle = 2.2 \times 10^{-9}\ M_\odot$ yr^{-1} which yields an average recurrence time of $T_{\rm R} = 2.3 \times 10^4$ yr. The absolute space density of classical novae in the galactic disk is then estimated to $\rho_{\rm CN} = 0.7 \pm 0.35 \times 10^{-6}$ pc^{-3}. A comparison with previous determinations and recent theoretical predictions is also carried out.

Key words: novae: space density – novae: recurrence time

1. Introduction

The problem of space densities of novae is still far from being solved. When counting the number of novae per unit volume in their quiescent state, one must include novae with unrecorded outbursts. Their identity, however, is not sufficiently well known to exclude severe under- or overestimates of their number. Alternatively, the space density may be calculated from the observed outburst density $\rho_{\rm out}$ of classical novae (CN) and the recurrence time of outbursts $T_{\rm R}$ according to

$$\rho_{\rm CN} = \rho_{\rm out} \times T_{\rm R} = \frac{N_{\rm out}}{\Delta T_{\rm obs}} \times T_{\rm R}\,. \qquad (1)$$

where $N_{\rm out}$ is the number of outbursts registered in a unit volume over the time interval $\Delta T_{\rm obs}$, and $T_{\rm R}$ the average recurrence period, for $\Delta T_{\rm obs} \ll T_{\rm R}$.

The recurrence time is found by indirect evidence. It can be obtained from the ratio of shell mass ejected during outburst (in $M_\odot$) to mean accretion rate during quiescence (in $M_\odot$ yr^{-1}) as derived from the disk luminosity at minimum and the mass of the accreting white dwarf. Recurrence times between 700 and 12000 years (average 3000 years) have been obtained this way (Duerbeck 1984). A somewhat different approach uses the ratio of total mass available for accretion from the secondary and shell mass to find the total number of outbursts. The total life time of the active nova stage divided by the number of outbursts yields recurrence times between 13000 and 26000 years (Patterson 1984).

If space densities are determined this way, assuming $T_{\rm R}$ to be of the order 10^4 years (being equivalent to the assumption that luminosities observed a few decades after outburst will prevail during the whole inter-outburst stage) it is found that a magnitude-limited sample in the solar vicinity should yield about ten times as much quiescent novae as are actually observed. Patterson (1984) confronts the "embarrassing" predicted number of 70 objects brighter than $11^{\rm m}$ with the five candidates observed. Duerbeck (1984) pointed out that a lowering of the luminosity, which also means a longer $T_{\rm R}$ and an even higher $\rho_{\rm CN}$, may be a way out of the problem. These findings, together with the fact that accretion rates derived from the luminosities of novae a few decades after outburst are uncomfortably high and do not permit thermonuclear runaways in sufficiently degenerate material, led to the introduction of the "hibernation scenario" (Shara et al. 1986): it is postulated that novae undergo varying accretion rates and spend a large fraction of their life in quiescence masked as other (fainter) types of cataclysmic variables (an idea already propagated by Vogt 1982), or even at such faint levels of luminosity that they are not included in the census of novae, quiescent novae, and potential nova candidates. Faint magnitudes are equivalent to low accretion rates, and recurrence times may be as long as 10^5 and 10^6 years. In this case, the space density of hibernating novae must be 10 to 100 times higher than that of novae which do not undergo hibernation. Nevertheless, they may hardly appear in magnitude-limited samples.

A critical discussion of previous results and a new independent determination of the space density of CN seem useful for the evaluation of current concepts.

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2. Problems

Major problems in estimating the absolute space density of CN are the following:

a) Recurrence time T_R

The observed quantity is the outburst density ρ_{out}, i.e., the number of outbursts N_{out} of CN per unit volume during a time interval of observations ΔT_{obs}. Contradictory estimates of T_R, derived by different methods, range from 1000 yr (Warner 1974) over the values quoted in sect. 1 to 10^{5-6} yr (Bath & Shaviv 1978). They account for the gross discrepancies in the values derived for ρ_{CN}.

b) Number of outbursts per unit volume N_{out} and total observing time ΔT_{obs}

Outburst densities based on statistics which include novae observed in the early decades of our century, should be taken with some caution. The number of recorded outbursts may be reduced by selection effects in the discovery of novae, i.e., loss of the faintest and fastest novae. Moreover, the volumes in which the measurements are taken, may appear larger or smaller, depending on under- or overestimates of the absorption towards each individual nova.

c) Different nova populations

The determination of ρ_{CN} is complicated by the fact that galactic novae might belong to different populations (Duerbeck 1990; Della Valle et al. 1992, hereafter DBLO92). It is found that intrinsically bright, large amplitude "disk novae", are concentrated towards the galactic plane within $|z| \leq 100$ pc, whereas faint, small amplitude "bulge novae", are found up to $|z| \approx 1000$ pc. If, according to our present understanding (e.g. Truran 1989; Livio 1992), this outburst behaviour reflects differences among the progenitor masses, the average recurrence period T_R is expected to be different for disk and bulge novae. Observational support for this dichotomy is the fact that disk and bulge of the Galaxy appear to produce novae at different rates (Della Valle 1992). Consequently, one should compute ρ_{CN} for each galactic sub-system separately.

These problems have motivated our study, which aims at finding the space density of CN in the galactic disk from their observed outburst rates and the estimated recurrence time of their outbursts.

3. State of the art

Warner (1974) determined the space density of CN after estimating the recurrence time of novae by extrapolating the Kukarkin-Parenago relation which combines such different systems as dwarf novae and recurrent novae. Although the physical basis of the method is obsolete, the value of the space density derived in this way, $\rho_{CN} \leq 10^{-6}$pc^{-3}, is not at large variance with some more recent determinations.

The very high space density of 10^{-4} pc^{-3}, derived by Bath & Shaviv (1978), has been criticized by Patterson (1984), Wheeler (1991), and Naylor et al. (1992). Its derivation is based on α, the fraction of white dwarfs that are primary components of nova systems. Naylor et al. have pointed out that Bath and Shaviv did not discriminate between the fraction observed today, α_{obs}, and the fraction born in nova systems α_{birth}. The lifetime of novae is much shorter than the lifetime of the Galaxy. Thus, old nova systems may have "evaporated", probably leaving single white dwarfs behind. The continuously increasing number of white dwarfs, in combination with a constant formation and decay rate of nova systems, makes α_{obs} a continuously decreasing quantity. Today, α_{obs} is probably a factor 100 smaller than α_{birth}. This factor directly enters into the determination of the recurrence time and the space density: Bath and Shaviv's recurrence time of several 100 000 years is reduced to several 1000 years and their space density ρ_{CN} is reduced from 10^{-4} to 10^{-6} pc^{-3}.

Patterson (1984) and Duerbeck (1984) studied galactic novae within 1000 pc from the Sun. The first author derived an outburst rate of $\rho_{out} = 1.7 \times 10^{-10}$ pc^{-3} yr^{-1} in a cylinder extending over 150 pc above and below the galactic plane. The second author fitted an exponential law $\rho_{out}(z) = \rho_{out}(0) \exp(-z/125)$, and derived the outburst density in the galactic plane $\rho_{out}(0) = 3.8 \times 10^{-10}$ pc^{-3} yr^{-1}. For comparison purposes, the density in the above cylinder can be calculated from this distribution, yielding $\rho_{out} = 2.5 \times 10^{-10}$ pc^{-3} yr^{-1}, in good agreement with the first result. The derived space densities $\rho_{CN} = (2.2 \ldots 4.4,$ and $0.75) \times 10^{-6}$ pc^{-3}, based on recurrence times of 13000 . . . 26000, and 3000 years, respectively, are still well within the same order of magnitude.

Searches for UV bright objects in the galactic plane yield, besides novae with recorded outbursts, also quiescent nova candidates (to be abbreviated QN) for which no outburst has been observed. Downes' (1986) low latitude survey recovered three novae with known eruptions (V603 Aql, GK Per, DI Lac), one dwarf nova (SS Cyg) and five novalike variables (NL). Specific absolute magnitudes were assigned to these objects; they are well-known for novae with nebular expansion parallaxes, fairly well known for the dwarf nova, and quite uncertain for the novalikes. The space densities were derived by Schmidt's (1968) method. Assuming that all novalikes found in his survey are novae with unrecorded outbursts (NL = QN), Downes derived the space density $\rho_{CN} = (0.57 \pm 0.24) \times 10^{-6}$ pc^{-3} for classical novae. This is a factor 2 – 7 smaller than the space densities derived by Duerbeck and Patterson under the assumption that recurrence times range between a few thousands to a few ten thousands of years (note that Downes quotes Patterson's density by a factor 10 too small). Vice versa, Downes used his space density $\rho_{CN} + \rho_{QN}$ together with the nova outburst density of Patterson to determine the recurrence time via eq.(1) to $T_R = 3350 \pm 1400$ yrs. Note, however, that in Downes' sample a noticeable percentage of novae, $(\rho_{CN})/(\rho_{CN} + \rho_{QN}) = 0.14/0.57 = 25\%$, has already suffered a nova explosion in the last 100 years, and a straightforward extrapolation would point to a recurrence time of a few hundred years (even under the optimistic assumption that all novalikes are quiescent novae, otherwise the recurrence time would be even shorter!).

When a true spread in T_R exists, samples are biased in favour of novae with frequent outbursts and the derived recurrence times are smaller than the true ones. Moreover, when there are "overlooked" quiescent novae, e.g. novae masquerading as dwarf novae (DN) or staying in hibernation, $\rho_{\rm QN}$ is larger than the density derived by Downes and so is the recurrence time. The small space density of DN determined by him indicates that the existence of quiescent novae disguised as dwarf novae will not increase $\rho_{\rm QN}$ significantly. Thus, we have to consider the possibility that Downes has underestimated the space density of novalikes by a large degree.

Shara et al. (1990) claim evidence for a space density of cataclysmic variables (CV) which is two orders of magnitude larger than that derived by Downes. They looked for UV bright objects in a $1^\circ \times 1^\circ$ region at galactic latitude $\approx +5^\circ$, and found 7 CV candidates down to $m_{\rm B} = 21$. Under the assumption that these objects have absolute magnitudes +8 to +10 (much fainter than those used by Downes, but justified by the fact that intrinsically brighter objects would have distances at which interstellar absorption reddens them to such a degree that they would not be discovered in the survey), they derive space densities for cataclysmic variables of all classes, $\rho_{\rm CV} = (70\ldots600)\times10^{-6}$ pc^{-3}. Thus, it seems established that there are many UV bright novalike systems intrinsically fainter than those found by Downes. If *all* these objects were hibernating novae, Patterson's and Duerbeck's values for $\rho_{\rm out}$ would yield recurrence times of several 10^5 to several 10^6 years. Certainly only a fraction of them are *bona fide* quiescent novae, and $T_{\rm R}$ must be smaller. A careful investigation of a volume limited sample of CV would be a possibility to identify quiescent novae and to determine $T_{\rm R}$ with some accuracy, but such a heroic effort has not yet been carried out.

4. A new approach

We have tackled the problem starting from the value of the galactic nova rate of 19 ± 6 novae/yr, recently derived using as calibrators the estimates of nova rates in external systems, M31, M33 and the LMC (Della Valle 1992). The second step is a comparison between the cumulative distributions of the rates of decline of the novae in the Galaxy, M31 and the LMC. Fig. 1 shows that the light curves of galactic novae mimic well the trend of the M31 nova population, but deviate strongly from the behaviour of the LMC novae, which are generally faster. This difference is even more significant because the number of fast novae in the LMC may be underestimated (DBLO92). Since the speed class of a nova critically depends on (a) the white dwarf mass, (b) the enrichment by heavy elements, and (c) the strength of the magnetic field, *the rate of decline ought to be regarded as a good tracer of intrinsic differences in the nova populations.* The majority of novae in M31 belongs to the bulge (Ciardullo et al. 1987), and a similar behaviour is expected for the galactic novae.

Capaccioli et al. (1990) have set a limit for the disk production of novae in M31 close to 20% of its global value. The close correspondence of the cumulative distribution of the Galactic novae to that of the M31 novae leads us to adopt the same percentage for them. However, if the Galaxy has a later Hubble type than M31 (van den Bergh 1988), its disk nova production may be slightly larger than that of M31. An independent estimate for the production of novae in the disk of the Galaxy can be derived from the sample of novae studied by Cohen & Rosenthal (1983) and Cohen (1985). DBLO92 noted indeed that about 35 % of the novae from this sample are both fast ($t_2 \leq 13^{\rm d}$) and bounded in a strip with $z \leq 100$ pc, and therefore belong to the disk. A similar fraction (~ 30%) arises from Duerbeck's (1984) compilation, which lists all novae within 1.5 kpc from the Sun. Since both investigations focus upon novae in the solar vicinity, they are biased towards novae belonging to the disk. 30% appears to be an upper limit for the percentage of disk novae. For the following discussion, we adopt 25 ± 5%.

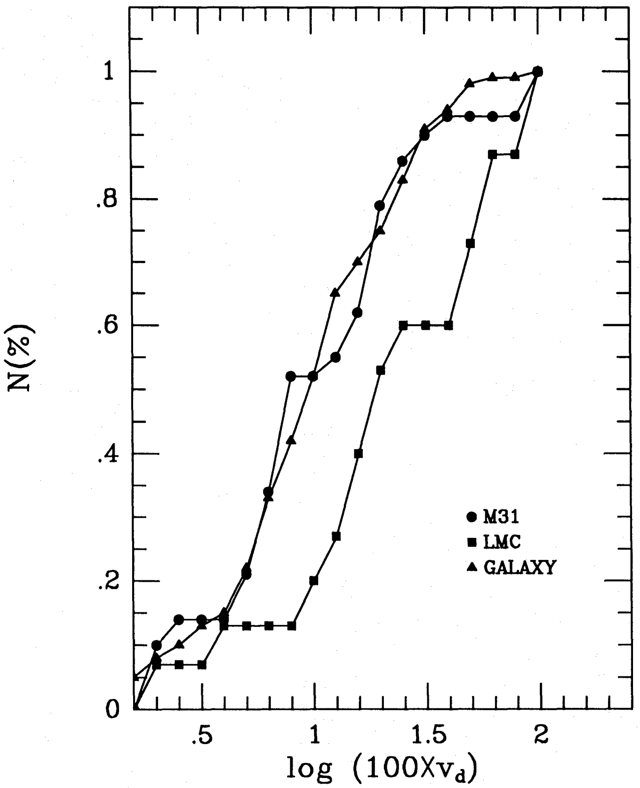

Fig. 1. Cumulative distributions of the rates of decline for M31, Galaxy and LMC. The M31 data come from Arp (1956) and Capaccioli et al. (1989), Galaxy data from Della Valle (1988), and LMC data from Capaccioli et al. (1990)

Thus, 5 ± 2.5 novae per year are produced in the disk of the Galaxy. Assuming a surface for the galactic disk of ≈ 850 kpc^2 (Ratnatunga & van den Bergh 1988) and a typical scale height of 100 pc, the volume occupied by disk novae is 170 kpc^3 and their outburst density is

$$\rho_{\rm out} = 0.30(\pm0.15) \times 10^{-10}\ {\rm pc}^{-3}\ {\rm yr}^{-1}\ (= \rho_{\rm CN}/T_R)\,. \qquad (2)$$

This value is smaller by a factor $\approx 6 - 30$ than the estimates of 2.5×10^{-10} pc^{-3} yr^{-1} (Duerbeck 1984), 1.7×10^{-10} pc^{-3} yr^{-1} (Patterson 1984) and $2.0\ldots8.8 \times 10^{-10}$ pc^{-3} yr^{-1} (Naylor et al. 1992) for novae in the neighborhood of the Sun. The discrepancy can be much reduced when these samples are decontaminated by removing the bulge novae. From Duerbeck's and

Patterson's compilations we derive an outburst density of disk novae of $(0.5 \pm 0.1) \times 10^{-10}$ pc^{-3} yr^{-1}, and from Naylor et al.'s approach, after considering only the novae produced in the disk of M31, instead of the global rate: $0.2 \ldots 0.9 \times 10^{-10}$ pc^{-3} yr^{-1}.

The agreement within a factor 2 – 3 is as more valuable as one considers that these results were derived from completely independent approaches, namely: counts in the solar neighbourhood (Duerbeck 1984; Patterson 1984), the revised approach of Bath & Shaviv (Naylor et al. 1992), and the global nova rate of the galaxy (this paper). The outburst density of CN is independent upon any *ad hoc* assumption about the recurrence time between the outbursts.

5. The quest for the recurrence times

We have derived the absolute magnitude at minimum for 91 galactic CN from the application of the maximum magnitude vs. rate of decline relationship (in the form discussed by Capaccioli et al. 1989), and the amplitude of the outburst. After dividing the data set into fast and slow novae, according to the prescription by DBLO92, we find that the absolute magnitude at minimum of CN is characterized (admittedly on the basis of a quite inhomogeneous database) by two different distributions (see Figs. 2 and 3). A Kolmogorov-Smirnov test (e.g. Press et al. 1986) supports indeed, at high level of significance (probability ≥ 99.8) the existence of such a difference in the distribution (Table 1).

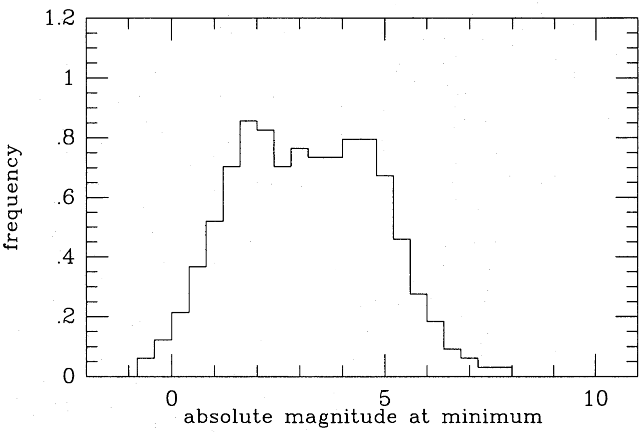

Fig. 2. Frequency distribution of absolute magnitudes at minimum for 67 slow novae (sample from Della Valle 1988)

Table 1. Average minimum magnitude of fast and slow novae

Nova class	N(objects)	$\langle M \rangle$	$\sigma/\sqrt{N}$
fast	24	4.8	0.33
slow	67	2.9	0.20

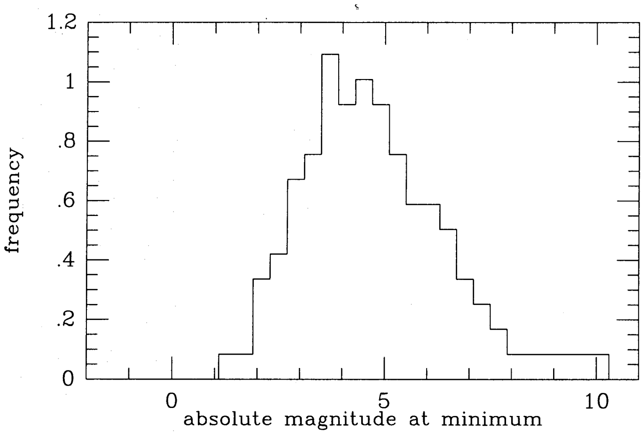

Fig. 3. Frequency distribution of absolute magnitudes at minimum for 24 fast novae. The curves are computed by sampling the data with a running gaussian window and normalizing at the same area

Under the assumption that the luminosity at minimum is generated by the accretion disk, we use the approximate formula (Webbink et al. 1987) to determine the accretion rate $\dot{M}$ in $M_\odot$ yr^{-1}:

$$M_v^{\min} \approx -9.5 - \frac{5}{3} \log \frac{M_{\rm WD}}{M_\odot} \times \dot{M} \,. \qquad (3)$$

Since the average absolute magnitude at maximum for disk novae as inferred by DBLO92 is $M_v^{\max} = -9.3$, the comparison with the results of Livio (1992, his Fig. 1) yields an average mass $M_{\rm WD}$ of about 1.2 $M_\odot$ for the white dwarf component in a fast nova. Then the average accretion rate for disk novae turns out to be

$$\langle \dot{M} \rangle = 2.2 \times 10^{-9} \; M_\odot \; {\rm yr}^{-1} \,. \qquad (4)$$

Under the assumption that the brightness of novae does not change dramatically during the time interval between the outbursts, an average recurrence time can be estimated by dividing the mass of the ejected shell by the accretion rate. The average hydrogen shell mass for those novae that can be assigned to the disk, taken from the determinations of Cohen & Rosenthal (1983) and Pottasch (1959), is 3.5×10^{-5} $M_\odot$. If this hydrogen is provided exclusively by mass transfer from the secondary, $\approx 5 \times 10^{-5}$ $M_\odot$ of matter have to be accreted. The accretion rate derived above, coupled with the "solar composition mass" of the ejected shell of $\approx 5 \times 10^{-5} M_\odot$, implies an average recurrence time of 2.3×10^4 yr for fast novae. Single objects may deviate by a large degree from this value, but we are interested only in an average value of the recurrence time. From eq. (2) and $T_{\rm R} = 2.3 \times 10^4$ yr, we derive a space density for CN (disk only) of $\rho_{\rm CN} = (0.7 \pm 0.35) \times 10^{-6}$ pc^{-3}. This is somewhat higher than Downes, in spite of the fact that Downes does include *all* types of novae and *all novalikes*. It was already noted that, despite its enormous merits, Downes' survey suffers from severe incompleteness, especially at the faint end. We have cross-checked a compilation of UBV photometry of cataclysmic variables (Bruch 1984) and find about twice as many objects with magnitudes brighter than 15.0 and $(U - B) < -0.5$, which should lie within the borders of Downes' survey, and there might even be more objects with UV excess for which no UBV photometry is available. When considering an incompleteness factor ≥ 3 in Downes' survey, his estimate of the recurrence time becomes $T_{\mathrm{R}} \geq 10^4$ yr, and therefore the discrepancy with the value of T_{R} derived here is sensibly reduced.

6. Conclusions

The main results of this paper may be summarized as follows:

(a) From the value of the nova rate of the Galaxy of ≈ 20 novae/yr, we infer that about 5 ± 2.5 novae/yr are produced in the disk. Then the space density of classical novae (divided by their recurrence time) in the galactic disk is $\rho_{\mathrm{CN}}/T_{\mathrm{R}} = (0.30 \pm 0.15) \times 10^{-10}$ pc^{-3} yr^{-1}. This number compares very well the values for the density of nova outbursts in the solar neighborhood (decontaminated by the presence of bulge novae) derived by several authors with independent approaches.

(b) The analysis of a sample of 24 fast galactic novae yields an average absolute magnitude at minimum of M_v = +4.8. This implies a mean accretion rate of $\langle \dot{M} \rangle = 2.2 \times 10^{-9}\ M_{\odot}$ yr^{-1} onto a typical WD progenitor of about $\langle M \rangle = 1.2\ M_{\odot}$. We note in passing that this is consistent with recent theoretical models of Prialnik & Kovetz (1992), who find that nova outbursts onto a 1.25 $M_{\odot}$ C-O WD are possible for an accretion rate of $\sim 10^{-9}\ M_{\odot}$. Assuming an average shell mass of $5 \times 10^{-5}\ M_{\odot}$ and the above reported accretion rate, we derive a recurrence time of 2.3×10^4 yr. After applying this to the outburst density, a space density $\rho_{\mathrm{CN}} = (0.7 \pm 0.35) \times 10^{-6}$ pc^{-3} is derived for classical novae in the disk.

This agrees within a factor 2 with Duerbeck's and Patterson's estimates (revised to take into account only the disk novae and the new recurrence time) and within a factor 1.5 with the space density derived from the theoretical estimate of the average column density of 5.5×10^{-9} novae pc^{-2} yr^{-1} in the solar neighborhood (Ritter et al. 1991; after assuming a recurrence time of 2.3×10^4 yr).

(c) The recurrence time $T_{\mathrm{R}} = 2.3 \times 10^4$ yr fits well the recurrence times computed for classical novae (Truran 1990) with massive white dwarfs ($M_{\mathrm{WD}} \geq 1.2\ M_{\odot}$). All this together supports the idea (Duerbeck 1990, DBLO92) that classical novae containing more massive white dwarfs are concentrated towards the galactic plane.

(d) To be consistent with the current estimates of the masses of ejected shells, the values of the accretion rate of $\langle \dot{M} \rangle = 2.2 \times 10^{-9}\ M_{\odot}$ yr^{-1}, and the recurrence time of $\approx 2 \times 10^4$ yr require a quasi-constant accretion rate during the interval of time between the outbursts. There are indications (Duerbeck 1992) that high-mass, short period post-novae show a secular trend to to become fainter, i.e. to decrease their mass-transfer. If this trend is a persistent one, the novae will enter hibernation and the "recurrence time" determined above represents *just a fraction* of the actual recurrence time between eruptions, and therefore it should be taken as representative of the time interval in which CN accrete at fairly high rate. Then, the derived ρ_{CN} has to be increased accordingly – as has the space density of low-luminosity novalike cataclysmic variables being novae in a hibernating stage. Observations like those reported by Shara et al. (1990), followed by detailed studies of discovered objects to determine orbital periods and white dwarf masses to isolate the hibernating novae, are the only way to determine the true space density of novae and the true recurrence time in a time interval that is shorter than T_{R}.

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