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ON THE FREQUENCY OF SUPERNOVA OUTBURSTS IN GALAXIES

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Recent systematic searches of supernovae have been used to determine their frequency in galaxies of different types. The average frequency is found to be about one supernova per 40 years, and appears to be of the same order in elliptical and spiral systems. For galaxies fainter than about $10^m.5$ there is a striking incompleteness of the discoveries, which increases steeply towards fainter magnitudes. This is the reason why lower numbers of supernovae have been found previously. The Galactic System shows roughly the same frequency of supernovae as the brighter galaxies. A brief discussion is given of the probable population characteristics of type I and type II supernovae.

1. Frequency of supernovae in external galaxies

For several reasons it seemed worthwhile to attempt a renewed discussion of the observational material bearing on the outbursts of supernovae in extragalactic systems. One of the things one is interested in is the frequency with which supernova outbursts appear. Another question is the relative frequency of type I and type II supernovae in different types of galaxies, and to which populations they should be assigned.

As an approach to the first problem we determined the fraction of galaxies in the Shapley-Ames catalogue (SHAPLEY and AMES, 1932) which during the interval 1885.0–1964.5 produced at least one supernova. This fraction has been computed for different types of galaxies and for different magnitude intervals, as is shown in tables 1 to 3. The magnitude system is that of the Shapley-Ames catalogue, while most morphological classifications were taken from the Reference Catalogue of DE VAUCOULEURS (1964), especially where the Shapley-Ames classification is doubtful. The following relation between the Hubble classification and the De Vaucouleurs system was used: E ≡ Elliptical, S0 ≡ Lenticular, Sa ≡ S0+S1, Sb ≡ S2+S3, Sc ≡ S4−S8.

The supernovae were counted in a list of supernovae discovered since 1885, prepared by Zwicky in 1964 as an interim report to the Committee for Research on Supernovae created by Commission 28 of the I.A.U. The fractions in table 3 refer to the whole sky. From the numbers in table 2 it is evident that, even in bright galaxies, the discovery of supernovae in the southern hemisphere has been much less complete than in the northern hemisphere: supernovae have been observed in 32 northern galaxies brighter than $12^m.6$, but in only seven southern ones. Furthermore, it is clear (cf. table 3) that the number of discovered supernovae per galaxy decreases rapidly with the apparent brightness of the galaxies.

Figure 1 illustrates the run of the computed fractions with magnitude for different types of galaxies. It is seen that, independent of the type of galaxy considered, the fraction decreases considerably for $m > 10.5$. This of course is an expected selection effect. It is probably mainly due to the better chances which the nearer

TABLE 1

Total numbers of galaxies in Shapley-Ames catalogue (whole sky)

Nebular type	$m \leq 10.0$	$10.0 < m \leq 11.0$	$11.0 < m \leq 12.0$	$12.0 < m \leq 12.5$
E+S0	3	19	77	87
Sa+Sb	7	10	62	58
Sc	8	24	106	126

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TABLE 2

Numbers of galaxies in which one or more supernovae have been found

Nebular type	δ	$m \leq 10.0$	$10.0 < m \leq 11.0$	$11.0 < m \leq 12.0$	$12.0 < m \leq 12.5$
E+S0	+	0	4	1	1
E+S0	−	0	0	0	0
Sa+Sb	+	1	2	1	1
Sa+Sb	−	0	1	1	0
Sc	+	1	3	10	7
Sc	−	2	1	2	0

TABLE 3

Fraction of galaxies in which at least one supernova has been observed (whole sky)

Nebular type	$m \leq 10.0$	$10.0 < m \leq 11.0$	$11.0 < m \leq 12.0$	$12.0 < m \leq 12.5$
E+S0	0.00 (0)	0.21 (4)	0.013 (1)	0.011 (1)
Sa+Sb	0.14 (1)	0.30 (3)	0.033 (2)	0.017 (1)
Sc	0.38 (3)	0.17 (4)	0.113 (12)	0.056 (7)
all types	0.22 (4)	0.21 (11)	0.061 (15)	0.033 (9)

galaxies offer for finding intrinsically fainter, and apparently more numerous, supernovae. The scanty data on maximum apparent magnitudes of supernovae in galaxies of different magnitude seem to confirm this expectation. Part of the effect may have been caused by the greater probability of discovering a supernova in a nearby galaxy because it can there be seen over a larger portion of its light-curve than in a more distant galaxy.

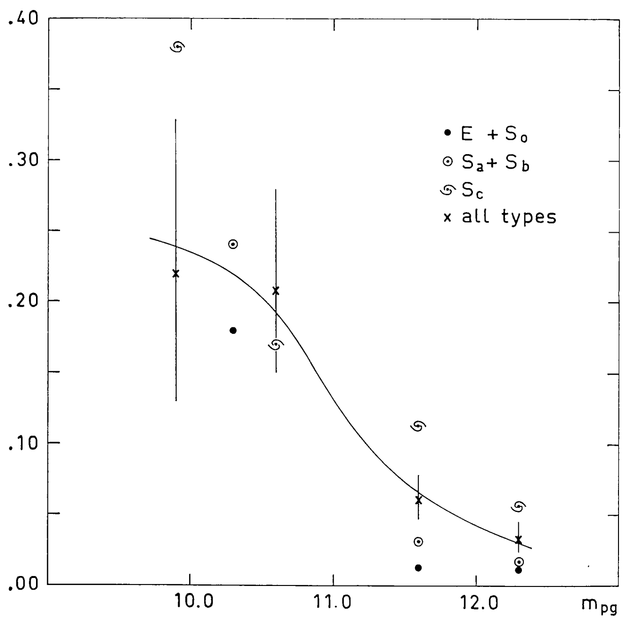

Figure 1. Fraction of galaxies in which at least one supernova has been observed against apparent magnitude. Mean errors have been indicated for the points referring to all types together (vertical lines).

Because the bright galaxies are concentrated to a considerable extent in the Virgo cluster and its extensions, it is conceivable that the *apparently* fainter galaxies might also be fainter *intrinsically*, and that the larger numbers of supernovae in the brighter galaxies might in part be due to a larger population of these systems. We have tried to investigate this by using the median radial velocities for the nebulae in the different magnitude intervals used in tables 1 to 3 as a distance measure. From the velocities in the catalogue by HUMASON, MAYALL and SANDAGE (1956) we find that in the magnitude range concerned the logarithm of the median velocity adheres closely to the relation $\log v = c + 0.20\, m$. There is thus no indication of a change in absolute magnitude with apparent brightness. This confirms the conclusion that the descent of the curve in figure 1 must be ascribed to the decreasing chance of discovery of supernovae in fainter galaxies.

For Sc-galaxies the frequency of supernovae decreases more slowly than for the other groups. The reason for this may well be the rather even surface brightness distribution in Sc-galaxies. One may detect supernovae in Sc-galaxies near the centre of the galaxy,

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which is not possible in early-type galaxies where one finds a sharp increase in surface brightness towards the centre.

For the determination of the true frequency of supernovae we have restricted ourselves to the northern hemisphere and to the galaxies of magnitude 11.0 and brighter. We have further restricted the statistics to the intervals 1936.0 to 1941.3 (I) and 1954.0 to 1964.5 (II) in which intensive searches were made, first by Zwicky and his collaborators (ZWICKY, 1942), and since 1956 by Zwicky and astronomers at several observatories in an international cooperation (cf. ZWICKY, 1965, p. 372). Even for the galaxies brighter than $11^{m}.1$ the frequency of discovery in these intervals was about three times higher than in the rest of the period since 1900. Though with the three restrictions mentioned the numbers that remain are small, the frequency estimated from these small numbers is the best we can do with the material available.

The numbers of supernovae found in each of the two periods are shown in table 4. It will be seen that the two intervals give practically the same result.

The annual number of supernovae per galaxy brighter than $11^{m}.1$ is given under $\langle n \rangle$ in table 5. The numbers in this table were obtained by combining those given in the second column of table 4 with the following numbers of galaxies in the northern hemisphere of magnitude 11.0 and brighter: 12 E+S0, 16 Sa+Sb and 21 Sc and Irr.

TABLE 4

Numbers of supernovae during intervals of intensive search (I: 1936.0–1941.3; II: 1954.0–1964.5)

Nebular type	$m \leq 11.0$		$11.0 < m \leq 12.0$		$12.0 < m \leq 12.5$	
	I	II	I	II	I	II
E+S0	1	2	1	0	0	1
Sa+Sb	1	1	1	1	0	1
Sc	1	4	3	6	2	4
all	3	7	5	7	2	6

TABLE 5

Numbers of supernovae per galaxy per year and the range in which the true frequency is likely to lie ($m \leq 11.0$, $\delta > 0°$; the observed numbers of supernovae are given in parentheses)

Nebular type	$\langle n \rangle$	Range
E+S0	0.016 (3)	0.009–0.028
Sa+Sb	0.008 (2)	0.004–0.016
Sc	0.015 (5)	0.010–0.023
all	0.013 (10)	0.009–0.018

There is a probability of about 2/3 that the real average will lie within the range indicated in the last column. According to this table a galaxy of a given apparent brightness would on the average produce one supernova per 80 years. The real frequency must be higher, as even in the years of the intensive survey some observable supernovae will have been missed. Firstly, not all northern galaxies brighter than $11^{m}.1$ have been surveyed, and, secondly, in those that were observed several supernovae must have escaped because their maximum light came in a season where the galaxy was unobservable. Moreover, in the spiral galaxies a certain fraction will have been invisible because of absorption. The true frequencies may conservatively be estimated to be one and a half times higher, giving, roughly, one supernova per 50 years.

The frequency of supernovae derived in this way is about ten times higher than estimated previously by Zwicky (cf. ZWICKY, 1942, and 1965, p. 378). As shown by the numbers in table 3 and figure 1 there can be little doubt that the difference is due to the great incompleteness of the discoveries of supernovae in fainter galaxies.

That the frequency of supernovae derived above must be of the right order is also borne out by the fact that during the period of about 65 years in which supernovae have been found five galaxies were observed to have three supernovae each, while two others had two supernovae. If the average frequency of supernovae per galaxy were only one per several centuries this would be utterly improbable. In fact, it was this large number of cases with several supernovae in one galaxy which started us on the statistics presented in this note. It may be noted that the five galaxies with three supernovae are all of the Sc-type and brighter than $12^{m}.0$; three of them are brighter than $11^{m}.0$.

We limit the discussion again to galaxies brighter than $11^{m}.1$ in the northern hemisphere, but include this time also the brightest galaxies in the southern hemisphere, viz. those brighter than $9^{m}.1$. We have then in total 25 Sc and Irr galaxies. It is evident that the galaxies in question will not have been observed constantly during the last 65 years, and that, therefore, supernovae will have been missed. We have computed the expected numbers of galaxies in which 0, 1, 2, 3 or

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TABLE 6

Expected and observed numbers of Sc and Irr galaxies having produced n supernovae

k	$t_{eff.}$ 43 years					$t_{eff.}$ 32 years				
	n 0	1	2	3	4	n 0	1	2	3	4
0.01	16	7	1.5	0.2	0.0	18	6	0.9	0.1	0.0
0.02	11	9	4	1.1	0.2	13	9	3	0.5	0.1
0.04	4	8	7	3.8	1.6	7	9	6	2.4	0.7
obs.	17	5	0	3	0	17	5	0	3	0

4 supernovae would have been observed if they had been effectively searched during two thirds or one half of the 65-year period, respectively. These expected numbers are shown in table 6, for three different values for the probability, k, that a galaxy will produce a supernova in a given year. The bottom line gives the observed numbers.

Comparing the computed and observed numbers we see that for $k = 0.01$ the probability of having 3 galaxies with 3 or 4 supernovae each is completely negligible, and that even for $k = 0.02$ this probability is small. From these numbers the true value of k would seem to be about 0.03, corresponding with an average of one supernova per 30 years. This evidence is to a considerable extent independent of that in table 5, as 5 of the 9 supernovae concerned were observed in years other than those covered by table 5.

If we look at the columns $n = 0$, 1 and 2 we see that, for $k = 0.02$ and 0.04, the observed numbers for $n = 0$ are too high, while for $n = 2$ they are too low. This might well be an effect of observational selection, galaxies in which two supernovae had already been found being watched more carefully than the others. The galaxies with more than two supernovae should then give a more trustworthy indication of the true frequency.

The galaxy NGC 6946 produced two supernovae very near to each other in 1917 and 1939. The projected positions with respect to the nucleus of the galaxy are:

1917: 105″ S, 37″ W;
1939: 105″ S, 30″ W.

It may well be that these supernovae, with a projected separation of about 140 pc, are related with one another. The photometric and colorometric investigation of NGC 6946 by BÖRNGEN *et al.* (1966) gives indeed an indication in this direction. At the position 105″ South, 30″ West of the centre of the nebula there is a very bright, blue region with dimensions of 150 by 150 pc. Compared to the neighbouring regions there is a brightness difference of about $0^m.5$ and a difference in colour index of about $0^m.25$ (0.77 instead of 1.05). So it is quite possible that these two supernovae originated in one and the same stellar association.

As far as one can judge from the scanty material in table 5 there is no striking difference in supernova frequency between E and S0 galaxies on one hand and spirals on the other hand. This is surprising because the supernovae in the elliptical galaxies are presumably population II objects, while in the spirals about half of them belong to population I, and must therefore have a completely different origin.

2. Supernovae in the Galactic System

It is of interest to compare the frequency of supernovae in other galaxies with what we know about supernovae in our Galaxy. The four cases where a supernova outburst has been observed to occur within the Galactic System are listed in table 7. We have not included η Carinae, which has been mentioned by Zwicky as a possible supernova, because its maximum intrinsic brightness was very much less than that of all other known supernovae, and resembles more that of ordinary novae. Though its outburst has not been observed we have added Cassiopeia A, because the ex-

TABLE 7

Data on galactic supernovae

Supernova	Year	l^{II}	b^{II}	Type	r (kpc)	$\|z\|$ (pc)
	1006	327.°6	+14.°6	I	1.3?	180?
Crab nebula	1054	184.3	− 6.2	II?	1.8	190
Tycho	1572	120.1	+ 1.4	I	5.0	130
Kepler	1604	4.5	+ 6.9	I	7 ?	800?
Cassiopeia A	≈1700	111.7	− 2.1	II	3.4	120

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pansion of the filaments connected with this radio source proves that it has exploded recently. For all other identified non-thermal galactic radio sources the explosion date lies very far in the past, or is entirely undeterminable, so that they are of no use for estimating the frequency of supernovae.

The types and distance estimates were taken from an unpublished typescript of an article by Minkowski on non-thermal galactic radio sources (MINKOWSKI, 1967), which the author kindly put at our disposal. The distances of the supernova of 1006 and of Kepler's star are given by the author as guesses rather than real estimates.

Leaving out the very distant supernova studied by Kepler, which may be situated in the central bulge of our Galaxy, we are left with four supernovae within 4 or 5 kpc from the Sun of which the outbursts have been recorded in a period of about 1000 years. If this frequency is representative for the whole galactic disk, with radius 15 kpc, it would give about 40 supernovae per 1000 years for the entire Galaxy, or one per 25 years. This frequency agrees rather well with that found above from the brighter galaxies. But we should keep in mind that some supernova outbursts within 5 kpc, like that of Cassiopeia A, will have been missed, so that the true frequency for the Galactic System may well be higher.

In an entirely different manner BLAAUW (1961) has arrived at a similar estimate for the frequency of population I supernovae in our Galaxy. From his very plausible theory concerning the origin of the "run-away" stars from massive close binaries of which one component has exploded as a supernova he concludes that there must have been about one supernova of this kind per 10^5 years within 1 kpc from the Sun, and, therefore, at least one per 1000 years for the entire Galaxy. The supernovae needed for this process must have had original masses of at least a hundred times the solar mass, in order to release the very massive run-away stars considered. It is likely that there will be many more supernova explosions of stars of more moderate mass. Blaauw estimates that the total number may be 10 times larger, giving a frequency of one type II supernova per 100 years. The factor is admittedly uncertain, but it is nevertheless interesting to note that the resulting frequency is of the same order as that found for type II supernovae in other spiral galaxies.

With a frequency of supernova explosions such as indicated these explosions may well be sufficient to account for the origin of cosmic rays in the Galactic System, as has been suggested by several authors (cf. GINZBURG and SYROVATSKII, 1964, 1967). There is now no longer any need to consider the Galactic System as being different from other systems in supernova production.

3. Population characteristics

The 15 supernovae in E and S0 galaxies for which spectral data are available are *all* of type I (cf. BERTOLA and SUSSI, 1965). It seems thus that stars belonging to population II can only produce supernovae of type I. It is not so evident that the reverse is also true, and that supernovae of type I are exclusively associated with population II. For supernovae with spectra which are clearly of type I occur also in late-type spirals, and, in fact, with about the same frequency as in ellipticals, though the number of population II stars in the Sc-galaxies must be much smaller than in the giant E galaxies. For the bright nebulae considered in the present article this is illustrated in table 8, the data for which were taken mostly from an article by PSKOWSKII (1962). It is also corroborated by the small sample in table 7. The same subject has been critically discussed by MINKOWSKI (1964). As BERTOLA and SUSSI (1965), and JOHNSON and MACLEOD (1963) have pointed out, the distribution of these type I supernovae within the galaxies shows no resemblance with the distribution of population II stars: they show no tendency whatever to be concentrated towards the centres of the spirals, and they have no halo distribution but appear to be mostly concentrated in the disks. It should be noted, however, that the lack of concentration towards the central regions may, at least partly, be due to a selection effect caused by the greater difficulty of finding supernovae in the brighter parts. The two type I *galactic* super-

TABLE 8

Numbers of supernovae of different types in galaxies brighter than $12^m.6$

Nebular type	Type I	Type II
E+S0	6	0
Sa+Sb	2	3
Sc	9	18

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novae within 5 kpc are likewise close to the galactic plane. From a study of the distribution of non-thermal galactic radio sources HARRIS (1962) has also reached the conclusion that supernovae lie close to the galactic plane. In this case there is some danger of a bias against supernovae in the halo, because these might have a much shorter life as a radio source than those exploding in the denser interstellar medium of the disk.

It seems that in the spirals most of the type I supernovae belong to a disk population, but that we cannot yet definitely decide whether it is an old or an intermediate-age disk population.

The status of the type II supernovae is less ambiguous. They have been found exclusively in spirals, and mostly in those of late type, where they occur in spiral arms (cf. BERTOLA and SUSSI, 1965). If the explosions needed to explain run-away stars are identified with supernovae of this type (cf. p. 243), one must infer that they belong to the extreme population I.

It remains a remarkable coincidence that explosions of such radically different types of stars as population II and population I supernovae are about equally frequent per galaxy.

Note added in proof

Since the above article was written we received Volume 1, No. 4 of *Astrophysics* with an English translation of an article on the frequency of supernovae by KUKARKIN (1965) and a comment by AMBARTSUMIAN (1965). They arrive at an even higher frequency of supernovae, viz. at least one per 15 years. They think that this high frequency—in particular for the galaxies in which several supernovae were observed—is connected with an exceptionally high intrinsic brightness, and thus a larger population, of these systems. Kukarkin discusses mainly the galaxies with more than one supernova, from which he derives an average interval of 16.5 years between successive supernovae, and concludes that for the intrinsically bright galaxies concerned the frequency must be greater than one per 15 years. We believe that this estimate is too high because the statistics are incomplete, in so far as galaxies of similar intrinsic and apparent brightness in which only one or no supernova appeared were disregarded. Our table 6 indicates that the true interval is probably about 30 years.

It is obvious that, other conditions being equal, smaller galaxies will produce less supernovae. The supernova frequency deduced in the present article refers to galaxies selected according to apparent magnitude. Apart from a possible effect due to the concentration of galaxies in and around the Virgo cluster (which effect appears to be small, cf. p. 240) the mean intrinsic brightness for galaxies of a given apparent magnitude m should not vary systematically with m, within the ranges considered here. From the relation given by HUMASON, MAYALL and SANDAGE (1956) for galaxies of all types the mean absolute magnitude for given m is found to be -19.2, if the Hubble constant is taken 100 km/sec · Mpc. For Sc-galaxies it is -19.0. We assume, therefore, that our estimated frequency of 1 supernova per 40 years refers to galaxies of this average absolute magnitude.

The absolute magnitudes of the five galaxies NGC 3184, 4303, 4321, 5236 and 6946, in which three supernovae have been observed do not deviate much from this average. NGC 4303 and 4321 lie in the central part of the Virgo cluster. Using for these large galaxies the integrated apparent magnitudes given under $B(0)$ in De Vaucouleurs' Catalogue, and adopting a distance modulus of 30.2 for the densest region of the cluster, we get $M_{pg} = -19.9$ for both galaxies. The other three galaxies have small velocities, between $+360$ and $+420$ km/sec relative to the galactic centre, so that we must use other distance criteria. For NGC 3148 and 6946 distances of 11 and 4 Mpc have been estimated by HODGE (1967) from H II regions; the corresponding values of M_{pg} are -19.6 and -18.0, respectively. The very bright southern galaxy NGC 5236 (M 83) is partially resolved according to De Vaucouleurs, and cannot therefore be more distant than 2 or 3 Mpc, giving $M_{pg} = -18.8$. We conclude that the average intrinsic brightness of these five galaxies is normal for galaxies down to a given apparent brightness.

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