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Spatial Distribution of Pulsars and Supernova Remnants*

A. O. Allakhverdiyev, O. H. Guseinov and I. M. Yusifov

Institute of Physics, Azerbaijan Academy of Sciences,
Narimanov Avenue 33, Baku 370 143, USSR.

Abstract

We show that the burst of Type I supernovas occurs about 10^8 years after the birth of the progenitor. This duration results in the main by the delay of the burst after the formation of a white dwarf of about one solar mass in a close binary system. The mass of the main component of this system is about $8\,M_{\odot}$, and the mass of the secondary about $3\,M_{\odot}$. These stars complete their evolution as Type I supernovas and are distributed along the galactic plane. Pulsars are formed about 10^7 years after the birth of their progenitors, and are accompanied by a Type II supernova. Pulsars therefore have an annular distribution in the Galaxy.

1. Introduction

The problem of Type I supernova (SN I) progenitors has been discussed for many years. We consider, similar to the majority of investigators, SN I to be connected with close binary stars (Whelan and Iben 1973; Tammann 1982; Miller and Chevalier 1983; Iben and Tutukov 1984). In Section 2 we pay attention to the delay time between the evolution of the primary component of a binary system and the SN outburst. This problem is solved on the basis of a consideration of the observational data. The spatial distribution of SNRs is also discussed. It is shown that SN I outbursts must also be connected with the regions of star formation.

The connection of pulsars with SN is now generally accepted. However, it is not definitely known whether the birth of all pulsars and, generally, of neutron stars is accompanied by an SN outburst. Guseinov and Kasumov (1973) argued against quiet collapse and we note (with pleasure) that no one presently claims that the birth-rate of pulsars exceeds that of SNRs. On the other hand, the majority of investigators refer to the total dissipation of a star in SN I outbursts. But not every Type II supernova (SN II) outburst is necessarily accompanied by the formation of a neutron star, let alone a pulsar. Then, what is the birth-rate of pulsars? How are pulsars distributed in the Galaxy? Section 3 is devoted to these and other questions on the statistical investigations of pulsars.

2. Time between an SN I Outburst and the End of Evolution of Its Progenitor

The surface density of SN I outbursts in spiral galaxies increases gradually toward the centre of galaxies (comparable with stars of spectral class B). SN II are similarly distributed, except towards the centre of galaxies, where the surface density falls

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(Tammann 1977; Guseinov *et al.* 1980). Hence, it follows that if SN I progenitors have masses $\sim 8 M_\odot$, the increase of surface density toward the centre of galaxies should be connected only with the delay time of explosion after the evolution of the massive component. For the majority of SN I this time is, evidently, $\sim 10^8$ yr, taking into account the small value of the gradient.

According to Barbon *et al.* (1984) three or more SN outbursts have been observed in eight Sc-type spiral galaxies in our century. In the galaxies NGC 4321, NGC 5236 and NGC 6946, four, five and six outbursts have been observed respectively. Of these 15 outbursts seven are confidently assigned to Type II and two are assigned to Type I. For the eight galaxies, out of 29 outbursts, 14 are confidently considered to be of Type II and seven of Type I. The ratio of rates of SN II and SN I in these galaxies over the last 20 years, when types of outbursts were established more certainly, remained the same as in the previous period. We recall that SN II at maximum have a smaller brightness than SN I and therefore they are more difficult to observe. On the other hand, the overwhelming majority of observed, but unidentified, outbursts in the galaxies considered can be referred to Type II, since Type I are a very uniform easily recognised group, so that all other outbursts are designated Type II. Hence, one can evidently assume that the ratio of the rates of SN II and SN I in Milky Way type galaxies during the periods of an increase in star formation rates is ~ 2–$2{\cdot}5$. If SN I were connected with only those massive stars which burst immediately at the end of their evolution, i.e. if there is no delay, then the ratio of rates could not be explained by bursts of star formation. Therefore, the observed increase in the ratio of SN II rates to those of SN I can be, most likely, connected with a delay between the birth of a star and its outburst as an SN. This fact shows that the fraction of SN I outbursts is large for systems existing for $\sim 10^8$–10^9 yr. During the bursts of star formation only that fraction of SN I which is connected with the burst of massive stars increases immediately after the end of evolution. These observational data testify to the fact that the mean delay time exceeds not only the lifetime of associations for $\sim 10^6$–10^7 yr, but also that of star formation regions of $\sim 10^8$ yr, at the same time being considerably less than 10^9 yr.

The observational data on outbursts in irregular galaxies are extremely scarce. Until 1984, in galaxies clearly classified as irregular, only 10 outbursts had been observed, eight of them being SN 1, one probably being SN II, and one uncertain (Barbon *et al.* 1984). In the galaxies NGC 5253 and NGC 4753 two outbursts of SN I were observed in each (Tsvetkov 1985). It has come as some surprise that, despite the large number of O stars in these galaxies, so few SN II outbursts have been observed: from the data on spiral galaxies one would expect 20 SN II for every eight SN I in these galaxies. This striking observational fact can be understood if one assumes that the ratio of rates of SN II outbursts to those of SN I is about one in irregular galaxies. One should suppose then that the overwhelming majority of OB stars in them are close pairs. A radio pulsar (Seward *et al.* 1984) is observed in the SNR G0540 − 69·3 of the Large Magellanic Cloud (LMC). Therefore, this SNR is, probably, the result of an SN II outburst. Thus, in irregular galaxies we face the difficulty of coincidence of great SN outbursts with a small number of stars which appeared long ago. Again the overwhelming majority of outbursts does not require a considerable delay ($\gtrsim 10^8$ yr).

Let us now consider the data on historical SNRs. Four SNRs out of six, excluding Kepler's SNR and the remnant of the SN 1006 outburst, are connected with star formation regions and five of them (except Kepler's SNR) are situated at a distance

<3 kpc (cf. Fig. 1). Evidently, within 5 kpc of the Sun a burst of star formation took place. It is clear that only massive parents and a small delay time can lead to such localising of SN outbursts.

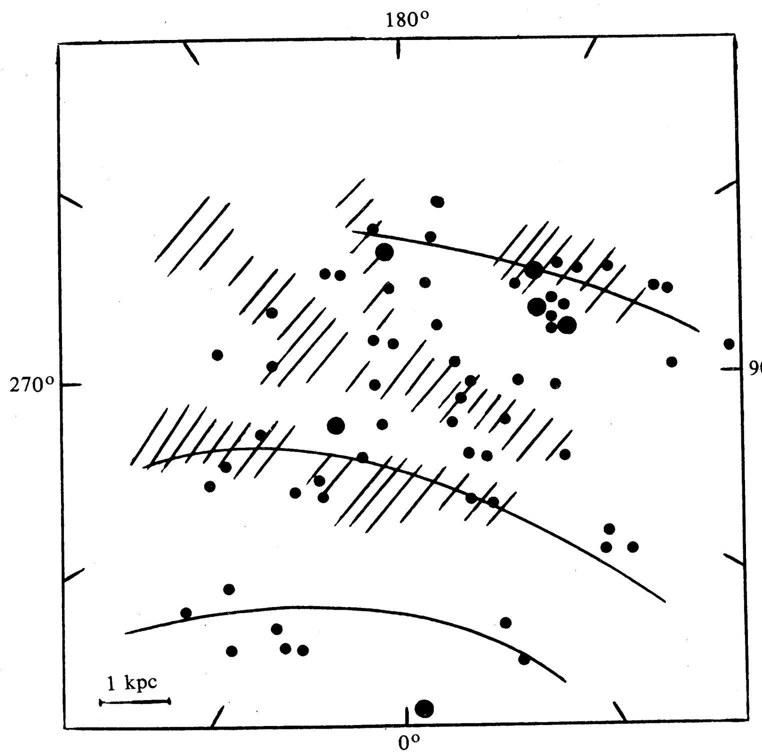

Fig. 1. Distribution of SNRs within 4 kpc of the Sun. Historical SNRs are given by the larger points. Star formation regions are hatched.

Usually, the SNRs Cas A (1667), Crab (1054) and 3C 58 (1181) are assigned to Type II, and Tycho (1572), Kepler (1604) and PKS 1459−41 (1006) to Type I. It is clear that the division of outbursts into types by restored light curves is rather uncertain. However, further studies have made the situation clearer. For Cas A, the estimates of a progenitor's mass ($M > 15 M_\odot$), the analysis of the chemical composition of the ejecta, and the location of a SNR inside the association Cas OB-2 clearly establish Cas A as Type II (Trimble 1982). The presence of a pulsar in the Crab SNR and of a point (X-ray) source in 3C 58 is, evidently, a good argument in favour of assigning them to Type II also (Trimble 1982). This certainly would be reinforced if they were situated in star association, but they are in star formation regions (see Figs 1 and 2) where ~20% of all O stars are located outside associations — a very large majority of O stars not belonging to associations. The SNR 3C 58 is located near two rich associations Cas OB-1 and Per OB-1. Hughes and Helfand (1985) on the basis of mass estimates and of the density of matter of Kepler's SNR drew definite conclusions on the large mass of the progenitor ($M > 7 M_\odot$). If correct, then the presence of a large amount of matter which earlier belonged to the star, which burst later and which did not scatter, reduces the delay time of the explosion almost to zero. The large intensity of X-ray emission favours assigning Tycho's SN to Type I. Tycho's SNR is projected on OB association Cas OB-4 with which it has equal velocity of rotation and distance in the Galaxy. Of course, errors in distance estimates are always much larger than the size of the associaton and they are therefore not necessarily physically connected. But the Crab Nebula and 3C 58, assigned Type II similar to the SNR 1006, are not projected on associations at all. Hence, one could say that the most massive stars, with shorter lifetimes than the associations, do not contribute significantly to the SN II outburst rates. This suggestion is supported by the fact that only half of the known SNRs within 4 kpc are projected on associations and, in principle, can be connected with them according to the available distance estimates.

On the basis of the analysis of SNR distribution (see Fig. 1) one can assume that the time necessary for a star from its birth to an outburst is, on average, $\sim 10^8$ yr and is less than 10^9 yr, since stars evolving for $\sim 10^9$ yr (i.e. those with masses $\sim$2–3 $M_\odot$) do not concentrate toward the star formation regions. A longer time ($\sim 10^9$ yr) is naturally needed for realisation of SN 1006 outbursts which, just like SNR G166·0+4·3 (within $\sim$4 kpc), is not connected with star formation regions. The star formation regions are also given by Guseinov and Yusifov (1987; this issue p. 831).

One can show that (1) for equality of the SN I and II rates in the Galaxy, the concentration of SN II outbursts in the vicinity of the Sun should be up to twice as large as that of SN I; (2) it is not at all necessary to assume the existence of a non-observed remnant of the outburst in the last millenium within 5 kpc; and (3) the overwhelming majority of outbursts in the region considered are concentrated in the star formation regions within 3 kpc. The strong non-uniformity in the distribution of outbursts in the Galaxy also testifies to the fact that the delay time of SN I outbursts is $\sim 10^8$ yr.

As one can see, the existing observational data favour the fact that the progenitors of SN I were stars with masses $\sim$6–8$M_\odot$ and the delay time of an outburst for the majority of them was $\sim 10^8$ yr. It means that in most cases SN I are the products of the evolution of a close binary system where the secondary component has a mass $\gtrsim 3 M_\odot$.

According to Tammann (1977) the SN I outburst rate in elliptical galaxies is, mass for mass, about 50 times less than in the Galaxy. These data also support the short scale of the delay time of an outburst.

From the above it follows that the SN I outburst occurs $\sim 10^8$ yr after the progenitor's birth. This time is mainly determined by the delay time of an outburst after the formation of a white dwarf with mass $\sim M_\odot$ in a close binary system. The primary component of this system has a mass $\gtrsim 6 M_\odot$, and the secondary one $3 M_\odot$.

It has usually been supposed that with the increase in the number of calibrators and in the accuracy of distance estimates, a more exact $\Sigma(D)$ dependence could be constructed for SNRs. However, Green (1984) having used calibrators with the most accurate distances found no exact $\Sigma(D)$ dependence for galactic SNRs. Moreover, he also confirmed this result by investigating SNRs in the Magellanic Clouds.

Allakhverdiyev *et al.* (1986) showed that on the basis of only one traditional criterion (namely, the accuracy of distance) in choosing calibrators, a $\Sigma(D)$ dependence cannot be obtained. This dependence can be obtained only if among the calibrators used a set of comparably evolving SNRs dominate, i.e. those which are found in approximately identical conditions of the medium. The distances to the remnants are estimated using the suggested simple $\Sigma(D)$ dependence and the data on the Galaxy and the SNRs themselves. The SNRs with small surface brightness are in various conditions of the medium and, apparently, they have no $\Sigma(D)$ dependence.

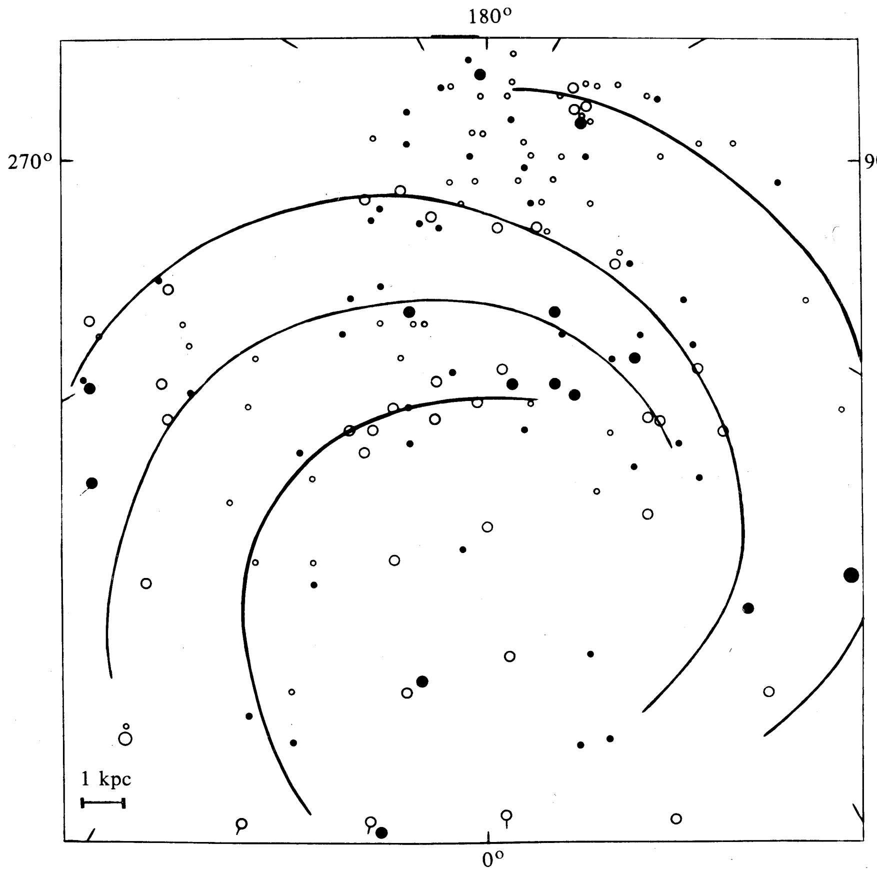

Fig. 2. Distribution of 146 SNRs in the Galaxy. SNRs with $\Sigma \geqslant 2\times10^{-20}\ \mathrm{W\,m^{-2}\,Hz^{-1}\,sr^{-1}}$ at $b \geqslant 0°$ are shown by open circles and at $b < 0°$ by solid circles. The size of each circle gives an indication of the strength of each SNR.

The distribution map of 146 SNRs is given in Fig. 2. The distance to the galactic centre is assumed to be 8·5 kpc. Fifty-four SNRs with $\Sigma_{1\mathrm{GHz}} \geqslant 2\times10^{-20}\ \mathrm{W\,m^{-2}\,Hz^{-1}\,sr^{-1}}$ are assigned large circles on the map. Their number is, apparently, 80–100 in the Galaxy. Many SNRs (especially plerions) are lost in connection with their projection onto giant HII regions (Allakhverdiyev *et al.* 1986).

3. Pulsars: Birth, Distribution and Evolution

In Allakhverdiyev *et al.* (1985) we made a thorough analysis of the pulsar distribution. New data from work on the detection of pulsars with large dispersion measure (DM) do not contradict their annular distribution (Clifton and Lyne 1987).

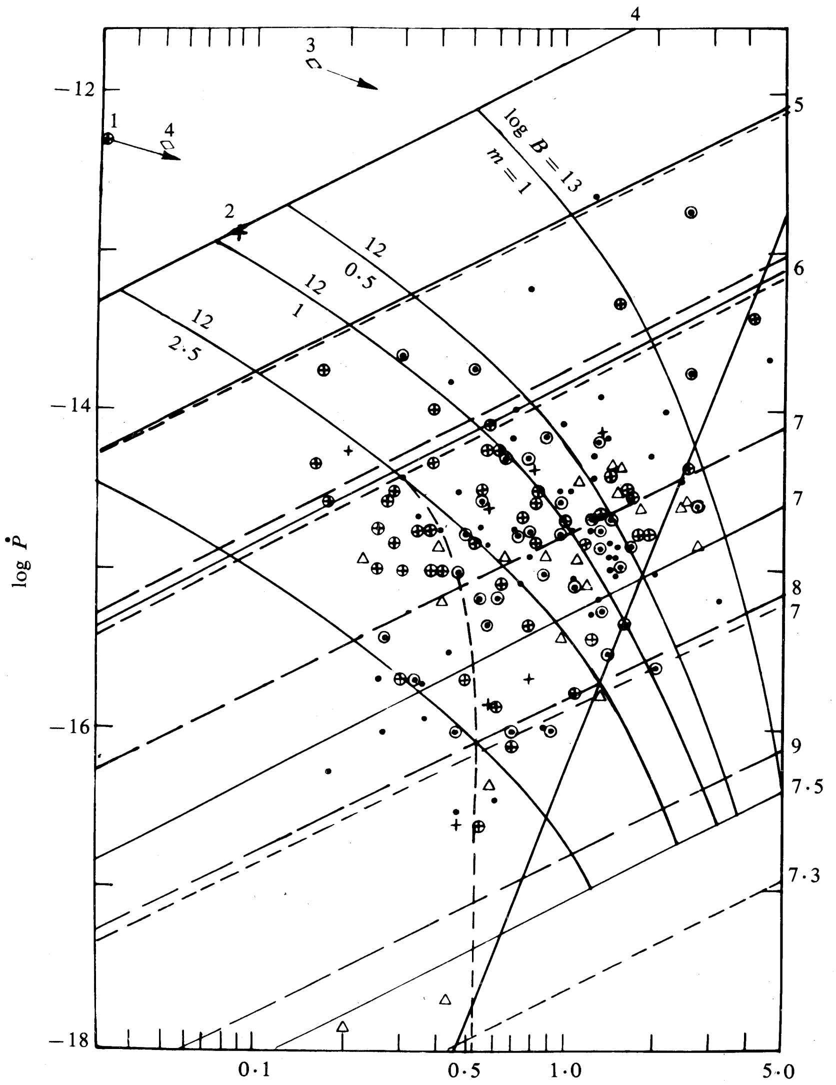

Fig. 3. The P–$\dot{P}$ diagram for pulsars. Pulsars located within 1 kpc of the Sun with $L \leqslant 10^{26}$ erg s^{-1} are marked by triangles, those with $10^{26} < L \leqslant 10^{27}$ erg s^{-1} by circles, and those with $L > 10^{27}$ erg s^{-1} by pluses. Pulsars with $1 < d \leqslant 2$ kpc are divided in the same ranges, shown with the same symbols and encircled. Solid curves show evolutionary tracks at a decay time of the magnetic field equal to 10^7 yr. Corresponding equal ages are shown by solid straight lines. The track and the lines of equal ages at the decay time of 5×10^6 yr are shown by broken lines. Lines of equal τ are shown by long dashes. The straight line crossing the lines of various ages is that of nulling. Pulsars located in SNRs are numbered.

The connection between pulsars and star formation regions and the distribution of electron density n_e in the vicinity of the Sun is shown by Guseinov and Yusifov (1987).

It is known that the lifetime of long-lived SNRs is less than the average lifetime of pulsars by about two orders of magnitude. Therefore, if one establishes the connection of a pulsar with a SNR, the young age of this pulsar is established at the same time. At present we have three pulsar–SNR pairs in the Galaxy, (1) PSR 0531+21/Crab, (2) PSR 0833−45/Vela XYZ and (3) PSR 1509−58/G320·4−1·4, as well as (4) one in the LMC (Seward *et al.* 1984). These pulsars with their corresponding numbers are shown on the P–$\dot{P}$ diagram in Fig. 3. For PSR 0531+21 and PSR 1509−58, the directions of evolution on the P–$\dot{P}$ diagram are also shown. These data are an essential argument in favour of the following: (i) τ at small values shows the true age of a pulsar satisfactorily and (ii) the correctness of the evolutionary tracks given in Fig. 3. The distribution of all pulsars in this diagram also testifies to the reliability of these evolutionary tracks and of the concentration of the younger pulsars in the upper lefthand corner. The pulsars are divided into three groups by their luminosities: pulsars with $L \leqslant 10^{26}$ erg s^{-1} (triangles), with $10^{26} < L \leqslant 10^{27}$ erg s^{-1} (circles) and with $L > 10^{27}$ erg s^{-1} (pluses). Pulsar luminosities were determined from the usual expression (see Manchester and Taylor 1981).

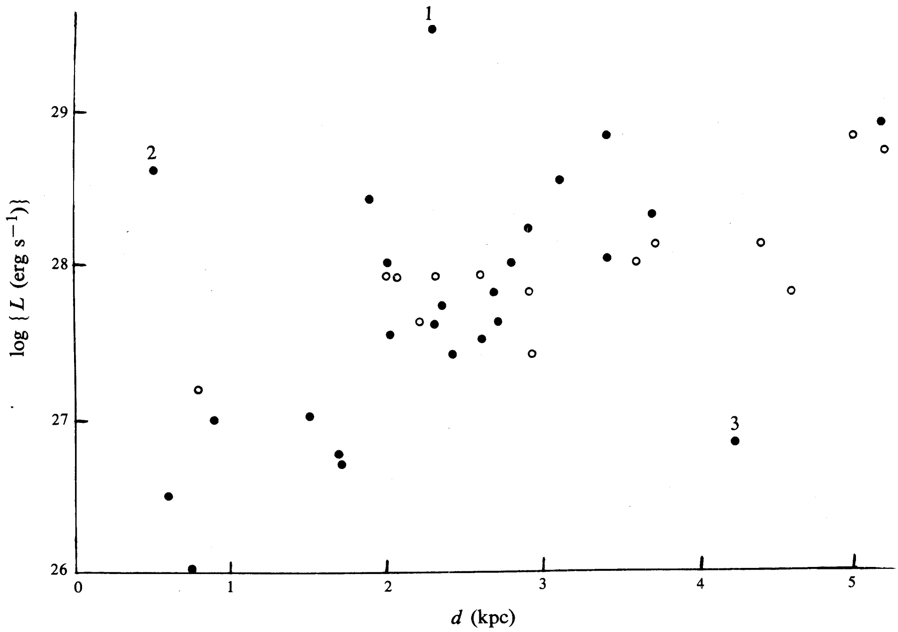

Fig. 4. Distribution of pulsars with $\tau \leqslant 10^6$ yr by L and d. Pulsars with $\tau \leqslant 5\times10^5$ yr are given by solid circles and those with $5\times10^5 < \tau \leqslant 10^6$ yr by open circles.

As is seen in Fig. 3, pulsars which evolve along boundary tracks, on the average, have smaller radio luminosities. The pulsar in the SNR G320·4−1·4 has $L = 5{\cdot}6\times10^{26}$ erg s^{-1}, i.e. more than one order of magnitude less than the pulsars numbered 1, 2 and 4. Note that this pulsar was first discovered as an X-ray pulsar. Among 28 SNRs located within 2 kpc, the presence of point X-ray sources has been determined reliably only for the Crab and Vela. One cannot exclude the connection of the SNR HB 9 with PSR 0459+47, which has the large value $\tau = 1{\cdot}8\times10^6$ yr. Point sources are projected on the SNRs G6·4−0·1, G74·0−8·5, G315·4−0·3 and G327·6+14·5 (Green 1984). With the beaming factor $K \approx 1/5$ in these 28 SNRs there should be about six pulsars emitting in our direction. Thus, what causes the difficulties in detecting close pulsars?

Luminosities of pulsars with $\tau \leqslant 10^6$ yr located within 5 kpc from the Sun are given in Fig. 4. Pulsars connected with SNRs are marked by the same numbers as in Fig. 3. As is seen from Fig. 4 young pulsars, i.e. with $\tau \leqslant 10^6$ yr, often have $L < 10^{27}$ erg s^{-1} and they are difficult to observe even at distances more than 2 kpc. Even if at small distances such pulsars are detected with difficulty within SNRs, then they must be detected after the remnants have scattered, i.e. after $\sim 10^5$ yr.

Recently Dewey *et al.* (1985) carried out a more sensitive search for pulsars and detected 34 new objects. Of these, only six according to our model n_e are located within 1 kpc of the Sun, and 21 within 2 kpc. Only one new pulsar was added to 15 known with $L \leqslant 10^{26}$ erg s^{-1} within 0·5 kpc. The rest of the newly detected pulsars with $L \leqslant 10^{26}$ erg s^{-1} are located at $0{\cdot}5 < d \leqslant 1$ kpc, where such faint objects were found before. According to the authors, in this search no pulsars with smaller luminosities than those known earlier were detected. That is why a 'turnover' of the luminosity function at $L < 10^{26}$ erg s^{-1} and the lack of pulsars with $L < 10^{25}$ erg s^{-1} may be considered as proved (Guseinov *et al.* 1981; Lyne *et al.* 1982, 1985). Approximately 400 SN must have burst during 10^6 yr within 2 kpc of the Sun, but only 12 pulsars with $\tau \leqslant 10^6$ yr are observed. If the beaming factor is $k = 1/5$, then in reality there must be about 60 pulsars within this radius. As seen in Fig. 3, fainter pulsars are located in the upper righthand corner at $\tau < 10^6$ yr. Besides, at large values of the period P the pulsars may have a considerably smaller beaming factor (Ruderman and Sutherland 1975; Kuzmin and Dagkesamanskaya 1983; Guseinov and Yusifov 1983). However, consideration of selection effects connected with small values of L and K does not save the situation. The number of pulsars with ages up to 10^6 yr connected with SN II must be $\sim$200. This discrepancy may be, in principle, removed if one accepts that $t = 10^6$ corresponds to $\tau \approx 1{\cdot}3\times10^6$ yr, and that the majority of pulsars have evolutionary tracks situated higher than the track of a pulsar with mass $M_\odot$ and magnetic field 10^{12} G. Apparently, the decay time of the component of the magnetic field perpendicular to the rotation axis and, generally, the lifetime of a pulsar with large H is small (Guseinov and Yusifov 1983). We do not know the reason for this phenomenon. However, we do not exclude the birth of pulsars at each, or almost at each, outburst of an SN II. The pulsar birth-rate in the Galaxy must be, apparently, between one in 70 and one in 150 yr.

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