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THE PULSAR LUMINOSITY FUNCTION

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RESUMEN

Hemos construido y examinado la función de luminosidad para pulsares, usando una nueva lista la cual incluye datos de 1328 radio pulsares. En este trabajo, se construye por primera vez la función de luminosidad en 1400 MHz. También presentamos una función de luminosidad mejorada en 400 MHz. Se comparan las funciones de luminosidad en 400 y 1400 MHz. De igual manera se construyen las funciones de luminosidad excluyendo los pulsares binarios y los de campos magnéticos pequeños. Se encuentra que la nueva función de luminosidad es considerablemente más plana en la parte débil en 400 MHz. Se presentan luminosidades en 1400 MHz para radio pulsares, junto con límites superiores para las luminosidades en 1400 MHz para pulsares anómalos en rayos-X, y para estrellas de neutrones débiles sin radio-emisión, como función tanto de la edad característica como del campo magnético. Se discuten las implicaciones de la función de la luminosidad de pulsares para estas nuevas clases de estrellas de neutrones.

ABSTRACT

We construct and examine the pulsar luminosity function using the new list which includes data for 1328 radio pulsars. In this work, the luminosity function for 1400 MHz is constructed for the first time. We also present an improved luminosity function for 400 MHz. The luminosity functions at 400 and 1400 MHz are compared. Also, the luminosity functions excluding the binary millisecond pulsars and the pulsars with low magnetic fields are constructed. It is found that the new luminosity function is considerably flatter in the low luminosity part for 400 MHz. 1400 HMz luminosity values of radio pulsars together with upper limits of 1400 MHz luminosity for anomalous X-ray pulsars and dim radio quiet neutron stars are presented as a function of both characteristic age and magnetic field. The implications of the pulsar luminosity function for these new kinds of neutron star are discussed.

Key Words: **PULSAR, AXP, SGR, DRQNS, SNR**

1. INTRODUCTION

In the last 30 years, radio-pulsar (PSR) luminosity functions have been constructed many times by different authors. From these works, it has been found that the 400 MHz luminosity function is a power law with slope 1.6–2.1 (see e.g., Guseinov & Yusifov 1986). Based on the Taylor, Manchester, & Lyne (1993) and Taylor et al. (1996) catalogue, Lorimer et al. (1993) constructed the luminosity function for $L_{400} > 10$ mJy kpc^2 and Allakhverdiev, Guseinov, & Tagieva (1997) constructed the luminosity function for $L_{400} > 1$ mJy kpc^2. Allakhverdiev et al. (1997) found the slope of the luminosity function to be 0.9 which is consistent with the slope given in Lorimer et al. (1993) within the error limits. Evidently, the error in the luminosity function is largely due to the fact that the number of PSRs with the highest and the lowest luminosities is small.

Data for 1328 PSRs are now available (Guseinov et al. 2003a). For 685 and 862 of them the flux values at 400 MHz and 1400 MHz are known. The number of PSRs with known 1400 MHz flux values has sharply increased because there have been many PSR surveys conducted at 1400 MHz (Johnston et al. 1995; Manchester et al. 1996; Sandhu et al.

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1997; Lyne et al. 1998; D'Amico et al. 1998; Lyne et al. 2000; Edwards & Bailes 2001a,b; Camilo et al. 2001; Edwards et al. 2001a; Edwards, van Straten, & Bailes 2001b; Manchester 2001; Manchester et al. 2002; Morris et al. 2002). The number of PSRs with log L_{1400} and log L_{400} less than zero has increased considerably. These data enable us to construct better radio luminosity functions for PSRs at 400 MHz, and for the first time at 1400 MHz.

The widely used definition of luminosity $L_\nu = F_\nu d^2$ mJy kpc^2 is adopted in this work. Evidently, it is also possible to use the luminosity for any frequency interval or for the whole radio band. On the other hand, the beam structure and the radiation flux distribution throughout the beam may have to be taken into consideration. However, in this case, new parameters with large uncertainties appear and the number of statistically reliable data decreases (Sieber 2002).

It is very important to know the amount of radiation emitted by a PSR in units of erg s^{-1} and the parameters on which the radiation depends (see Malov & Malofeev 1994; Guseinov & Yusifov 1986). However, in this work, we are concerned with another important problem: the determination of the number distribution of PSRs as a function of luminosity at two different radiation bands, i.e., at 400 and 1400 MHz. The non-detection of PSRs in some supernova remnants (SNRs) and the non-detection of radio radiation from anomalous X-ray pulsars (AXPs), soft gamma repeaters (SGRs) and dim radio quiet neutron stars (DRQNSs) might be due to the radio luminosity function of neutron stars. If this is true, we have to know how the luminosity function influences these non-detections.

In § 2, we present the luminosity function for all radio PSRs at 400 and 1400 MHz. In § 3, we present the luminosity function for PSRs with characteristic ages $\tau < 10^7$ yr, so that the millisecond binary PSRs and PSRs with low magnetic fields are excluded. In the last section, we discuss the implications of our work in the light of current theory and observations.

2. LUMINOSITY FUNCTION FOR ALL PULSARS AT 400 AND 1400 MHZ

Figure 1 displays the log L_{400} vs. distance distribution for PSRs closer than 1.5 kpc. The PSRs farther than 1.5 kpc are excluded so as to obtain a sample with large enough numbers of low luminosity PSRs and to have the PSR distances in the sample be less uncertain. In the volume up to 1.5 kpc, L_{400} values are known for 114 PSRs. For 12 of them log $L_{400} < 0$. In Figure 2, Log L_{1400} vs. distance is displayed for PSRs closer than 1.5 kpc. In the volume up to 1.5 kpc, L_{1400} is measured for 101 PSRs and 33 of them have log $L_{1400} < 0$. No farther PSRs are known with such low luminosity values in the Galaxy. As seen in Figs. 1 and 2 there are enough PSRs with low luminosity to construct realistic luminosity functions for both frequencies down to low luminosities.

Figure 3 displays separately the luminosity function for PSRs with known flux values at 400 MHz and at 1400 MHz. In Figures 3 and 4, N represents the number density of PSRs which have luminosity values equal to or greater than an arbitrarily chosen value. The number density of PSRs in each chosen interval of luminosity can be found by the change in log N in that luminosity interval. We fit the luminosity function at 400 MHz by using three different lines. The dependence of log N on log L_{400} has a sharper slope for log $L_{400} > 1.5$ and can be expressed as:

$$N = 520\ L_{400}^{-0.85\pm0.01}\,. \tag{1}$$

The portion of the luminosity function for luminosity values in the range $0.2 <$ log $L_{400} < 1.5$ is fitted by the equation:

$$N = 62\ L_{400}^{-0.19\pm0.01}\,, \tag{2}$$

and for lower luminosity values ($-0.5 < \log L_{400} < 0.2$) by

$$N = 57.5\ L_{400}^{-0.071\pm0.006}\,. \tag{3}$$

The slope in equation (1) is consistent with the slopes given by Lorimer et al. (1993) and Allakhverdiev et al. (1997) within error limits. But, as the luminosity decreases, the slope of the luminosity function for log $L_{400} < 1.5$ continuously becomes flatter. Therefore, the number of PSRs with small luminosities does not increase as sharply as expected. Actually, the slope of the lowest luminosity part of the luminosity function must be somewhat sharper as shown by the dashed lines in Figs. 3 and 4. Below we will discuss this problem.

For the luminosity function at 1400 MHz, we fit the luminosity function by using three different lines. The high luminosity part (log $L_{1400} > 0.5$) of the luminosity function is fitted by the expression:

$$N = 188.4\ L_{1400}^{-0.95\pm0.02}\,. \tag{4}$$

In the interval $-0.5 <$ log $L_{1400} < 0.5$, the fitting function becomes:

$$N = 85.1\ L_{1400}^{-0.27\pm0.01}\,, \tag{5}$$

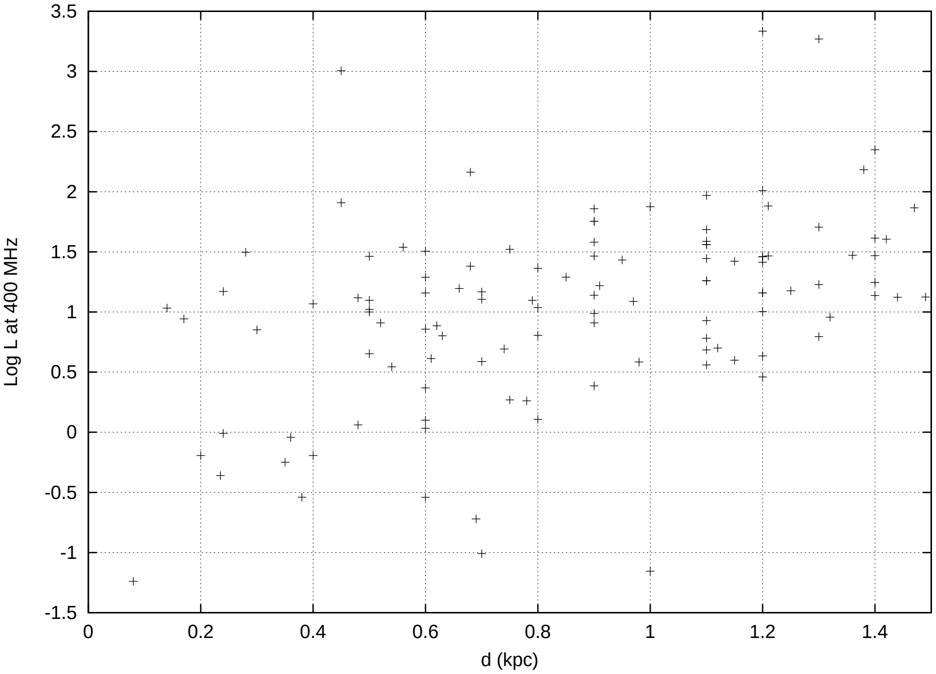

Fig. 1. Luminosity of PSRs at 400 MHz (L_{400}) vs. distance (d) values from the Sun for 114 PSRs up to 1.5 kpc.

and for smaller values of the luminosity ($-1 < \log L_{1400} < -0.5$), the luminosity function has a smaller slope and is given by the expression:

$$N = 101\ L_{1400}^{-0.13\pm0.01}\,. \tag{6}$$

Each data point in Figs. 3 and 4 is calculated as the average of PSR number density in three different volumes centered on the Sun. These volumes are chosen such that there are enough PSRs for a fixed luminosity so that the largest volume contains up to the most luminous PSRs and the smallest volume contains the least luminous PSRs. The errors are calculated as the deviation of these values from the average values for these three volumes. We find the number densities of PSRs corresponding to the luminosities larger than or equal to each luminosity value.

3. LUMINOSITY FUNCTION FOR SINGLE PULSARS WITH CHARACTERISTIC AGES $\tau < 10^7$ YEARS

To exclude the binary millisecond PSRs and the PSRs with small values of magnetic field, we choose the PSRs having $\tau < 10^7$ yr and construct the luminosity function. The number of PSRs with $\tau < 10^7$ yr and having flux observed at 400 MHz is 364, but in the region up to 1.5 kpc from the Sun, the number is only 44. The luminosity function for this sample of PSRs is given in Fig. 4. As seen from this figure, for Log $L_{400} < 0$, the slope of the luminosity function approaches zero. For higher luminosity values ($\log L_{400} > 1.5$), the luminosity function is given by the expression:

$$N = 158.5\ L_{400}^{-0.65\pm0.02}\,, \tag{7}$$

but the portion of the luminosity function in the interval $0.4 < \log L_{400} < 1.5$ can be fitted with the expression:

$$N = 52.5\ L_{400}^{-0.31\pm0.01}\,. \tag{8}$$

The total number of PSRs with $\tau < 10^7$ yr and having fluxes observed at 1400 MHz is 562, whereas in the volume around the Sun up to 1.5 kpc it is 35. As seen from Fig. 4, the part of the luminosity function with the luminosity values $\log L_{1400} > 0.3$ is fitted by:

$$N = 66\ L_{1400}^{-0.72\pm0.10}\,. \tag{9}$$

The luminosity function for PSRs with fluxes known at 1400 MHz and for PSRs with $\tau < 10^7$ yr is constructed here for the first time; therefore, there is no other published luminosity function available for comparison.

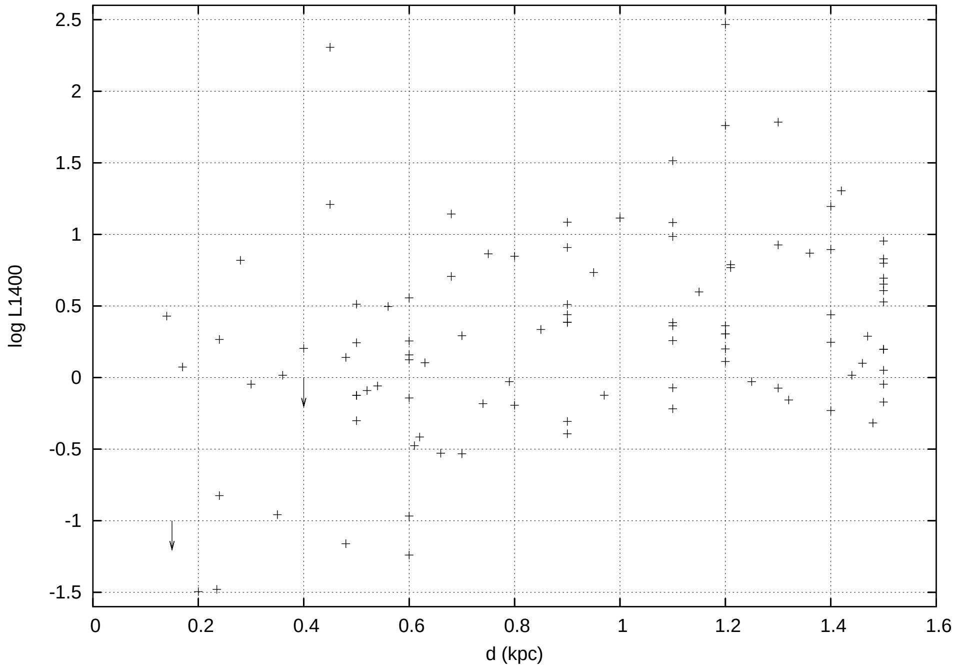

Fig. 2. Luminosity of PSRs at 1400 MHz (L_{1400}) vs. distance (d) from the Sun for 101 PSRs up to 1.5 kpc

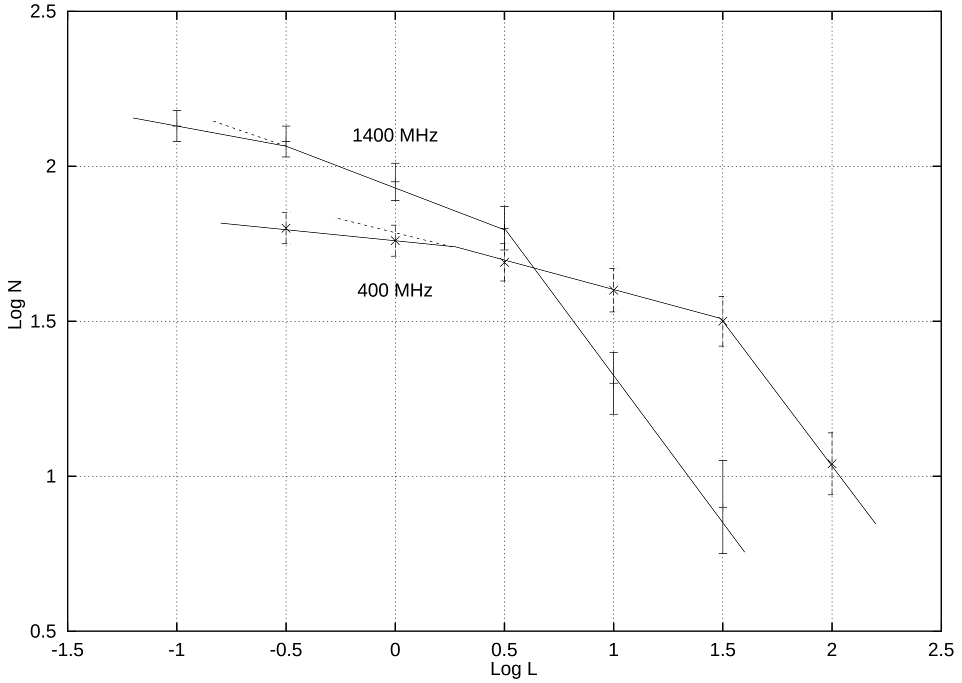

Fig. 3. $\log N - \log L$ dependence for all PSRs for 400 MHz and 1400 MHz, separately.

4. DISCUSSION AND CONCLUSIONS

4.1. *Luminosity Function for Radio Pulsars*

In § 2 and § 3, the luminosity function is presented for PSRs observed at frequencies of 400 and 1400 MHz. Luminosity functions are constructed both for all PSRs and for the PSRs with characteristic ages $< 10^7$ yr. Previously, the luminosity function for 1400 MHz could not be constructed because the number of PSRs observed at this frequency

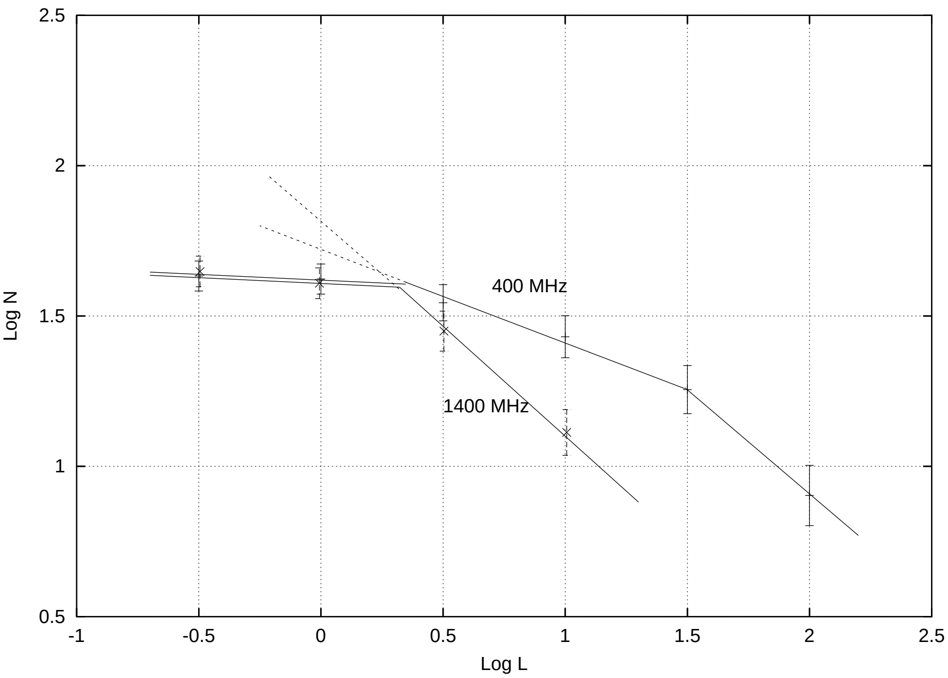

Fig. 4. $\log N - \log L$ for single PSRs with characteristic ages $< 10^7$ yr.

was too small. As is known, using the luminosity function, the ratio of the space density of PSRs with different luminosities can be determined. For this reason, we are only interested in the form of the luminosity functions. To find the real density of PSRs in any luminosity interval, the function must be calibrated by considering the number density of PSRs which have luminosities higher than a chosen value.

It is necessary to remember that at 1400 MHz a huge part of the Galactic plane is scanned thoroughly and with high sensitivity. At 400 MHz, however, the Galaxy is scanned thoroughly and precisely only within the Arecibo window ($40^o < l < 65^o$; $|b| < 2.5^o$) (Hulse & Taylor 1974, 1975), so that some low luminosity PSRs might not have been detected. The above fact might explain the flatness of the low luminosity parts of the luminosity functions at 400 MHz. However, to obtain a more trustworthy result, more statistically reliable data are necessary.

4.2. *Radio Luminosity of Anomalous X-ray Pulsars and Soft Gamma Repeaters*

The upper limits of radio fluxes at 1400 MHz for AXPs are known (Gaensler et al. 2001). But, since these objects are located far from the Sun, their detection threshold is high. In Figure 5 and 6, log L_{1400} values versus log τ and log B for PSRs, AXPs and DRQNSs with ages $< 3 \cdot 10^5$ yrs are presented. As seen from these figures, the radio luminosities of young PSRs practically do not depend on τ or B. Upper limits for the radio luminosities of 4 AXPs are, on the average, smaller than those of young PSRs. AXPs 1E2259+586, and 4U0142+625 have very small upper limits for the radio luminosity. However, these data provide only weak evidence on the absence of radio radiation emitted from these objects, since the radio beam might not be in our line of sight.

4.3. *Radio Luminosity of Dim Radio Quiet Neutron Stars*

In Figs. 5 and 6 we do not use DRQNSs with period P> 5.5 s because they have lower value of the voltage. As seen from the figures, this class of neutron stars practically does not have any radio radiation, or else the radio beams of these sources are not in our line of sight. The number of known PSRs younger than 10^5 yr up to the distance 1 kpc is 2 (Guseinov et al. 2003a). The number of DRQNSs with such ages and distances is at least 5. Among these sources, for two of them upper limits for radio fluxes at 1400 MHz (see Table 1 and Guseinov et al. 2003b) are known. This may be an indication that the birth rate of DRQNSs in the Galaxy must be closer to or higher than the birth rate of known radio PSRs. This situation may change if we take the beaming factor into account. The beaming fac-

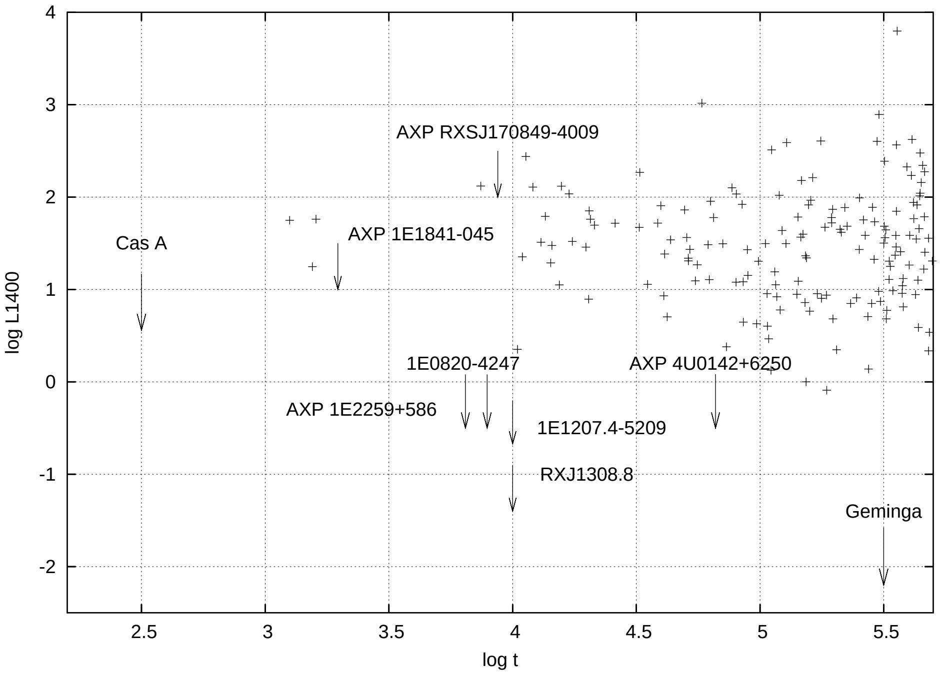

Fig. 5. The radio luminosity versus characteristic ages (Log L_{1400} − log τ) for young PSRs and for different types of single point X-ray sources.

TABLE 1

PARAMETERS OF DRQNSs[a]

Source	SNR	P (s)	τ or t (kyr)	d (kpc)	S_{1400} (mJy)	log L_{1400}	Ref.[b]
1E1207.4–5209	G296.5+10.0	0.424	7	2.1	< 0.2	< -0.2	[1–8]
1E0820–4247	G260.4–3.4	0.075	2	2	< 0.3	$<$ 0.08	[7,9–12]
CXO J2323+5248	G111.7–2.1	···	0.3	3.2	< 1.3	$<$ 1.2	[1,13,14]
RX J1308.8+2127	···	5.16	6–12	~ 0.4	< 0.94	< -0.8	[15]
Geminga	···	0.237	350	0.16	< 1	< -1.5	[7,16–19]

[a] With small upper limits for luminosities at 1400 MHz and with known τ or SNR ages, t.

[b] 1). Pavlov et al. 2002a; 2) Giacani et al. 2000; 3) Pavlov et al. 2002b; 4) Mereghetti et al. 1996; 5) Vasisht et al. 1997; 6) Kaspi et al. 1996; 7) Brazier & Johnston 1999; 8) Roger et al. 1988; 9) Pavlov et al. 1999; 10) Gaensler et al. 2000; 11) Becker et al. 1995; 12) Petre et al. 1996; 13) Reed et al. 1995; 14) Kaplan et al. 2001; 15) Hambaryan et al. 2002; 16) Halpern & Holt 1992; 17) McLaughlin et al. 1999; 18) Caraveo et al. 1996; 19) Seiradakis 1992.

tor for very young radio PSRs (e.g., Crab PSR) is $\sim 1/2$ and practically all X-ray PSRs in SNRs are found to emit pulsed radio radiation. It is necessary to remember that PSR J0205+6449 was known as DRQNS RXJ0201.8+6435 until recently (Camilo et al. 2002).

The luminosity functions we have constructed are not free from the effect of the beaming factor. It is a possibility that the beaming factor for radio PSRs decreases with age. Then the low luminosity parts of our luminosity functions must have a slope a few times higher. As we have indicated above, the birth rate of DRQNSs in the Galaxy is not less, and is possibly higher, than the birth rate of PSRs. If we assume that DRQNSs have the same physical nature as radio PSRs, then it is almost certain that the low luminosity part of the luminosity function including DRQNSs must have a higher slope, as shown in Figs. 3 and 4 with dashed lines. It is necessary to take into account the fact that two SNRs which con-

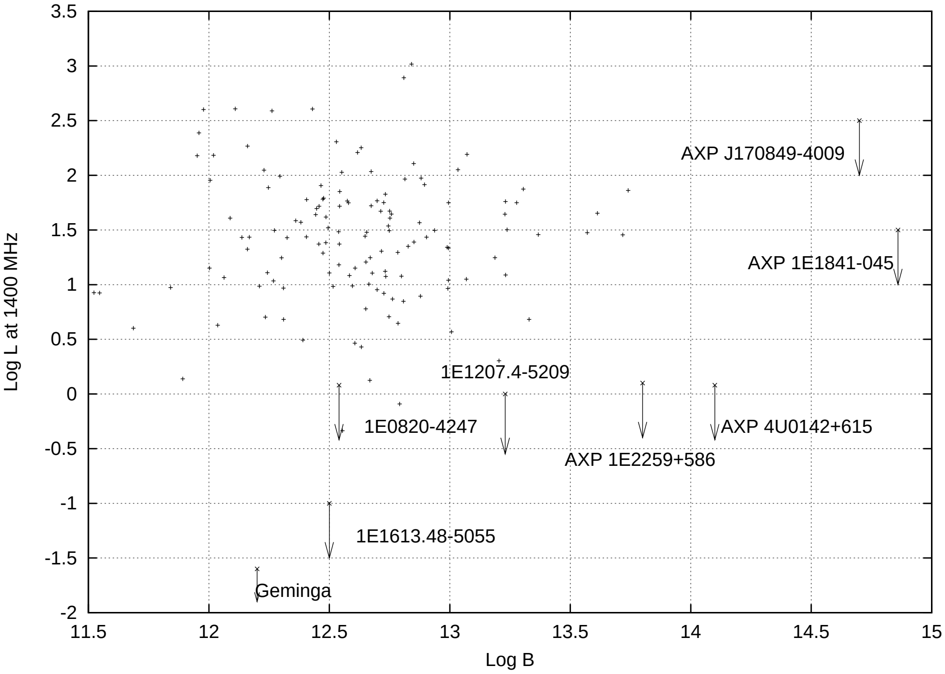

Fig. 6. The radio luminosity versus magnetic field strengths (Log $L_{1400} - \log B$) for young PSRs ($\tau < 3\ 10^5$ yr) and different types of single point X-ray sources.

tain AXPs and 7 SNRs which contain DRQNS are all S (shell) type, but the SNRs which contain PSRs are mostly C (composite) or F (filled center) type independent of their radio fluxes (see e.g., Green [2001] for the description of SNR types). But C and F type SNRs contain PSRs with large values of rotational energy loss $\dot{E}$. There are also some DRQNSs having similar values of $\dot{E}$. It is a possibility that DRQNSs may be a type of NSs which is different from PSRs. Due to the above fact it is not easy to adopt that idea. But still we cannot rule out that possibility.

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