Pulsar Luminosity Function

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Abstract. We construct and investigate the pulsar luminosity function using the new catalogue which includes data for 1315 radio pulsars. The luminosity functions are constructed for 400 and 1400 MHz separately, and they are compared. Also, the luminosity functions excluding the binary millisecond pulsars and other pulsars with low magnetic fields are constructed. The 1400 MHz luminosities as a function of characteristic age and as a function of magnetic field for radio pulsars, anomalous X-ray pulsars and dim radio quiet neutron stars are presented and the implications of the pulsar luminosity function on these new kind of neutron stars are discussed.

Key words. Pulsars, AXPs, DRQNSs

1. Introduction

As known, radio pulsars (PSRs) do not radiate isotropically, but radiate in a beam. The beaming angle in the radio band is much less than the ones in the X-ray band (Lyne \& Graham-Smith 1998). Now, we have the data for 1315 PSRs (Guseinov et al. 2002a). From these PSRs, about 30 of them with characteristic ages $\tau < 10^7$ yr are observed also in optical, X-ray and $\gamma$-ray bands. Becker \& Trümper (1997) gives the list for 19 radio PSRs with ages $\tau < 10^7$ yr observed also in the X-ray band with the \textit{ROSAT} satellite.

For the last 10 years, very important objects in astrophysics; so called soft gamma repeaters (SGRs), anomalous X-ray pulsars (AXPs) and dim radio quiet neutron stars (DRQNSs) has been investigated very intensively (Mereghetti et al. 1996; Kaspi et al.)
There is no radio radiation observed from these sources (Gaensler et al. 2001). Some of these single neutron stars, namely, SGRs and AXPs have X-ray spin periods between 5-10 s and their magnetic field strengths are believed to be $B=10^{14}-10^{15}$ G (Thompson & Duncan, 1995). It is believed that the age of AXPs and SGRs absolutely are not more than $10^5$ yr (Tagieva & Ankay, 2002). Since PSRs with characteristic time $\tau < 10^5$ yr have magnetic fields mostly of $10^{12}-10^{13}$ G and since no PSR has a magnetic field as high as $10^{14}-10^{15}$ G, AXPs and SGRs are named as magnetars. It is important to note that now the properties of AXPs and SGRs are mostly investigated in the frame of the magnetar model, however, we do not know definitely that these neutron stars have such huge magnetic fields. We wonder whether the non-detection of radio radiation from SGRs, AXPs and DRQNSs with spin periods $P \sim 5$-10 s is due to the strong magnetic fields?

There are about 10 dim X-ray point sources. Some of these sources with small periods are connected to supernova remnants (SNRs) (see Gaensler et al. 2001 and Tagieva & Ankay 2002 for review). There is no radio radiation detected from these sources in spite of their small distances from the Sun. We may expect that the reason that there is no radio radiation from DRQNSs with small periods is because of the radio luminosity function.

For most of the SNRs closer than 5 kpc, there have been searches for pulsars (Gorham et al. 1996, Lorimer et al. 1998). However, it has been very hard to detect them. Up to 5 kpc from the Sun, only 6-7 pulsars are found to be genetically connected to SNRs (Kaspi & Helfand 2002, Camilo et al. 2002, Guseinov et al. 2002b). Most of them are discovered in surveys. There are about 79 SNRs up to the distance 5 kpc (Guseinov et al. 2002b). This shows that on the average, for SNRs closer than 5 kpc, only 1 genetic connection exists for 11-13 SNRs. Is not this a result of the luminosity function and background radiation? In this paper, we aim at finding the improved luminosity function at 400 MHz and for the first time at 1400 MHz which is more important today due to the fact that the radio observations of AXPs, SGRs and DRQNSs are conducted at 1400 MHz. We also aim at investigating the properties of the luminosity function for all PSRs and single born PSRs, separately.

### 2. Luminosity Function For All Pulsars at 400 and 1400 MHz

In the last 30 years, PSR luminosity functions are constructed for many times. Most of them have been done by different authors between the years 1975-1981. From these works which are appropriate, it has been found that the 400 MHz luminosity function has a power law form with slope $-\left(1.6-2.1\right)$ (see Guseinov et al. 1982 for a review). After the publication of Taylor et al. (1996) catalogue, Lorimer et al. (1993) constructed the luminosity function for $L_{400} > 10$ mJy kpc$^2$ and Allakhverdiev et al. (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 within the error limit of the slope given in Lorimer et al. (1993). Evidently, the error in the luminosity function is high due to the fact that the number of PSRs with the highest and the lowest luminosities is few.

From 1315 PSRs, for 685 of them the flux value exists at 400 MHz, and for 862 of them the flux value exist at 1400 MHz (Guseinov et al. 2002a). The number of PSRs having flux data measured at 1400 MHz sharply increased because of the observations of the sky (mostly the galactic plane in the southern sky) is conducted at that frequency in the last years (Lyne et al. 2000; Camilo et al. 2000; D’Amico et al. 2001, Edwards & Bailes 2001). The number of PSRs with Log L$_{1400}$ and Log L$_{400}$ less than zero have considerably increased. We have indicated the importance of the luminosity function for PSRs with low luminosity in the introduction. Figure 1 displays the Log L$_{400}$ vs. distance distribution for PSRs closer than 1 kpc. In the volume up to 1 kpc, L$_{400}$ values are known for 70 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. For both of the frequencies there are enough number of PSRs with low luminosity. This provides us with the opportunity to construct the luminosity functions for both frequencies down to low luminosities realistically. Figure 3 displays the luminosity function for PSRs with known flux values at 400 MHz. In Figure 3, N represents the number density of PSRs which have luminosity values equal to or greater than the luminosity value corresponding to N. As seen from the figure, there is not one linear relation between Log N and Log L$_{400}$. We have fitted the luminosity function by three different linear approximations. Log N dependence on Log L$_{400}$ has a sharp slope for Log L$_{400} > 1.5$ and have the expression:

$$N = 520L_{400}^{-0.81\pm0.01}$$ (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:

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

and the slope for lower luminosity values (-1<Log L$_{400} <0.2$) is given by the expression:

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

The slope of the dependence (1) in error limits is consistent with slopes given in Lorimer et al. (1993) and Allakhverdiev et al. (1997). But the slope of the luminosity function for Log L$_{400} <1.5$ continues to get more flat, therefore, the number of PSRs with small luminosities do not increase as strong as we think before.

Figure 4 displays the luminosity function for PSRs with flux values known at 1400 MHz. Again, we have fitted the luminosity function with three different lines for three dif-
different luminosity intervals. The high luminosity part (Log L_{1400} > 0.5) of the luminosity function is fitted by the expression:

\[ N = 188.4 L_{1400}^{0.55\pm0.01} \]  

(4)

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

\[ N = 85.1 L_{1400}^{-0.27\pm0.01} \]  

(5)

and at smaller values of luminosity (-1.5 < Log L_{1400} < -0.5), the luminosity function have a smaller slope given by the expression:

\[ N = 101 L_{1400}^{-0.13\pm0.01} \]  

(6)

The data points in Figure 3 and 4 are calculated as the average of PSR number density in three different volumes. These volumes are chosen such that there are enough number of 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.

3. Luminosity Function for Single Pulsars with Characteristic Ages \( \tau < 10^7 \) Years

As mentioned in the introduction the radio fluxes for SGRs and AXPs are unknown or for some of these sources upper limits are known (Gaensler et al. 2001). This is also true for DRQNSs (Halpern et al. 2002; Mereghetti et al. 1996; Vasisht et al. 1997; Brazier & Johnston 1999; Petre et al. 1996; Walter et al. 1996; Neuhauser et al. 1997; Kaspi et al. 1996; Motch 2000; McLaughlin et al. 1999, 2000; Roger et al. 1988, Kaspi et al. 1998; Hambaryan et al. 2002; Lorimer et al. 1998; Seiradakis 1992; Kassim & Lazio 1999; Shitov et al. 1997; Malofeev & Malov 1997; Ramachandran et al. 1998). If for SGRs and AXPs the non-existence of radio luminosity is due to the very high magnetic fields, then what is the reason that DRQNSs with small periods have very low radio luminosity? For most of the single neutron stars born with magnetic fields of \( 10^{11}-10^{13} \) G, PSR luminosities seem not to be related with the strength of the magnetic fields of such single PSRs. We wonder whether there are differences in the radio radiation properties of PSRs and SGRs/AXPs/DRQNSs and can their radio luminosity be predicted from the luminosity function of PSRs? To answer these questions and to avoid the influence of the binary millisecond PSRs, we constructed the luminosity function for the single born PSRs.

To exclude the binary millisecond PSRs and other PSRs with small values of magnetic field strength, we took the PSRs having \( \tau < 10^7 \) yr and constructed 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 \( d < 1.5 \) kpc from the Sun, their number is only 44. The
luminosity function for this sample of PSRs is given in Figure 5. As seen from the figure, for \( \log L_{400} < 0.5 \), the slope of the luminosity function approaches to zero. For higher luminosity values (\( \log L_{400} > 1.5 \)), the slope of the luminosity function is given by the expression:

\[
N = 158.5 L_{400}^{-0.63 \pm 0.02} \tag{7}
\]

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

\[
N = 52.5 L_{400}^{-0.31 \pm 0.01} \tag{8}
\]

The total number of PSRs with \( \tau < 10^7 \) yr and having flux observed at 1400 MHz is 562 but in the volume around the Sun with radius of d<1.5 kpc is 35. As seen from Figure 6, the part of the luminosity function with luminosity values \( \log L_{1400} > 0.3 \) is fitted by:

\[
N = 66 L_{1400}^{-0.75 \pm 0.10} \tag{9}
\]

For lower values of luminosity \( \log L_{1400} < 0.3 \), the luminosity function has a slope given by the equation:

\[
N = 40 L_{1400}^{-0.05 \pm 0.01} \tag{10}
\]

The luminosity function for PSRs with fluxes known at 1400 MHz is constructed for the first time, therefore there is no other luminosity function published for comparison.

### 4. Discussion and Conclusion

In Sections 2 and 3, the luminosity function is found for PSRs with luminosity known at 400 and 1400 MHz. Luminosity functions are found both for all PSRs and for PSRs which are born single and have characteristic ages \( < 10^7 \) yr. Before, the luminosity function for 1400 MHz could not be constructed because the number of PSRs observed at this frequency was few. Now since the number of such PSRs are 862 in the Galaxy (Guseinov et al. 2002a), we constructed the luminosity function at 1400 MHz. To compare the luminosity functions in Figures 3-6, we brought them together in Figure 7. As known, using the luminosity function, the ratio of space density of PSRs with different luminosities can be determined. To find the real density of PSRs in any luminosity interval or PSRs with luminosities higher than any given luminosity, the function must be calibrated by considering the number density of PSRs which have luminosity higher than a chosen luminosity value. In Figure 7, we calibrated the luminosity functions such that they have the same values at \( \log L = -1 \). Using this function we may have information about the relative number of PSRs with different values of luminosity values.

As seen from Figure 7, the luminosity function for single born PSRs (lines 5 and 6) and luminosity function for all PSRs (lines 3 and 4) are similar at the same frequencies.
There is huge difference when we compare the luminosity functions at 400 and 1400 MHz. The reason of this huge difference is that the spectral index of PSRs is sharp. By comparing the lines 3 and 5 in the figure, we see that the number density of PSRs which are born single with Log L_{400} close to 1.5 is less but number density of single PSRs with Log L_{400} ~ 0-0.5 is more. On the other hand, if we compare the lines 4 and 6 we see that single born PSRs with Log L_{1400} > 0.5 is more. There might be some doubts in the comparison of the line 3 and 5 which are closer to each other, however, the results obtained by comparison of the line 4 and 6 are must be trustworthy.

If the AXPs and SGRs are magnetars then the non-detection of radio radiation from them must be explained. If AXPs are accreting neutron stars, then they will not emit any radio radiation. The upper limits of radio fluxes at 1400 MHz for AXPs are known (Gaensler et al. 2001). In Figure 8 and 9, Log L_{1400} values versus Log $\tau$ and Log B for PSRs with ages $< 3 \times 10^5$ yr are represented. As seen from these figures, the radio luminosities of PSRs practically do not depend on $\tau$ or B. Upper limit values for radio luminosities of 4 AXPs on the average are smaller than that of young PSRs. AXPs 1E2259+586 and 4U0142+625 have very small upper limits for luminosity. As we see from Figure 6 number of PSRs with such small luminosity must be very small. Therefore we may believe that AXPs and may be also SGRs have very small radio luminosity.

In Figures 8 and 9 also upper limit for radio luminosities of DRQNSs are presented. As seen from figures, without any doubt, this class of neutron stars practically do not have radio radiation. The Number of PSRs younger than $10^5$ yr up to the distance 1 kpc is 2. The number of DRQNSs with such ages and distances is also 2. This shows that the birth rate of DRQNSs in the Galaxy must be closer to the birth rate of radio PSRs. This situation does not change if we take the beaming factor into account. The beaming factor for radio PSRs is $1/2$ which implies the number of radio PSRs younger than $10^5$ yr and closer than 1 kpc to be 4. CHANDRA satellite observations will considerably increase the number of known DRQNSs.

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Figure 1. Distribution of luminosity of PSRs at 400 MHz ($L_{400}$) vs. distance values from the Sun for 70 PSRs up to 1 kpc.

Figure 2. Distribution of luminosity of PSRs at 1400 MHz ($L_{1400}$) vs. distance from the Sun for 101 PSRs up to 1.5 kpc.
Figure 3. Log $N$ - Log $L_{400}$ dependence for all PSRs. The numbers in the figure represent the degree of the slope.

Figure 4. Log $N$ - Log $L_{1400}$ dependence for all PSRs. The numbers in the figure represent the degree of the slope.
Figure 5. Log N - Log $L_{400}$ dependence for single PSRs with characteristic ages $< 10^7$ yr. The numbers in the figure represent the degree of the slope.

Figure 6. Log N - Log $L_{1400}$ dependence for single PSRs with characteristic ages $< 10^7$ yr. The numbers in the figure represent the degree of the slope.
Figure 7. All Luminosity functions together.

Figure 8. The radio luminosity versus characteristic ages (Log $L_{1400}$-Log $\tau$) for young PSRs and for different types of single point X-ray sources.
Figure 9. The radio luminosity versus magnetic field strengths (Log $L_{1400}$-Log $B$) for young PSRs ($\tau < 3 \times 10^5$ yr) and different types of single point X-ray sources.