Effects of the background radiation on radio pulsar and supernova remnant searches and the birth rates of these objects

Aşkın Ankay\textsuperscript{1} *, Oktay H. Guseinov\textsuperscript{1,2} †, Sevinç O. Tagieva\textsuperscript{3} ‡

\textsuperscript{1}TÜBİTAK Feza Gürsey Institute, 81220 Çengelköy, İstanbul, Turkey
\textsuperscript{2}Akdeniz University, Department of Physics, Antalya, Turkey
\textsuperscript{3}Academy of Science, Physics Institute, Baku 370143, Azerbaijan Republic

Abstract

In different directions of the Galaxy the Galactic background radio radiation and radiation of complex star formation regions which include large number of OB associations have different influences on radio pulsar (PSR) and supernova remnant (SNR) searches. In this work we analyse the effects of these background radiations on the observations of PSRs at 1400 MHz and SNRs at 1000 MHz. In the interval $l=0^\circ\pm60^\circ$ the PSRs with flux $F_{1400}>0.2$ mJy and the SNRs with surface brightness $\Sigma>10^{-21}$ Wm$^{-2}$Hz$^{-1}$sr$^{-1}$ are observable for all values of $l$ and $b$. All the SNRs with $\Sigma>3\times10^{-22}$ Wm$^{-2}$Hz$^{-1}$sr$^{-1}$ can be

\* e-mail: askin@gursey.gov.tr
\† e-mail: huseyin@gursey.gov.tr
\‡ email: physic@lan.ab.az
observed in the interval $60^\circ<l<300^\circ$. We have examined samples of PSRs and SNRs to estimate the birth rates of these objects in the region up to 3.2 kpc from the Sun and also in the Galaxy. The birth rate of PSRs is about one in 200 years and the birth rate of SNRs is about one in 65 years in our galaxy.

Key Words: Radio background, radio pulsar, supernova remnant, star formation region
1 Introduction

Although the problem of birth rates of radio-pulsars (PSRs) and supernova remnants (SNRs) has been discussed for many years, it is still an open question. The main difficulties in solving this problem are the selection effects in observations. It is not well known under which circumstances single PSRs are born under a supernova (SN) explosion. Actually, PSRs may be born under SN explosions of types Ib, Ic and II (here we do not consider the accretion induced collapse). SNRs are formed as a result of SN explosions with energies $10^{49}-10^{51}$ erg, and in some cases, even with energies several times smaller than $10^{49}$ erg (e.g. Crab, Sollerman et al. 2000) and with energies $>10^{51}$ erg (e.g. Cas A, Vink et al. 1998; Wright et al. 1999).

According to Lorimer et al. (1993) PSRs are formed once every 150 years in the Galaxy and the lower limit for the mass of the stars which form PSRs at the end of their evolution is about $5 \, M_\odot$. By examining the historical SNRs, Strom (1994) found that a SN explosion occurs every 6 years in the Galaxy and the lower limit for the mass of the progenitors of these SNRs is also about $5 \, M_\odot$. There is an unlikely large difference between the birth rate of PSRs given by Lorimer et al. (1993) and the formation rate of SNe given by Strom (1994). Does the formation of PSRs predominantly depend on some other parameters because of the lower limit for the progenitor mass being the same in both cases?

It is known that in Sb-type galaxies rate of SN explosion is similar to the SN rate in our galaxy, $\sim 1\text{-}2$ in 100 years on average, because our galaxy also is Sb-type. (van den Bergh & Tammann 1991). Recent statistical investigations of SN rate in Sb-type galaxies show that the rate of SN Ia is $0.4 \pm 0.2$ in 100 years and the rate of SN II together with SN Ib and SN Ic is about $1.5 \pm 1.0$ per century in Sb-type galaxies and so in our galaxy (Capellaro et al. 1999; Capellaro & Turatto 2001).

In our galaxy no evidence was found of a SN explosion in the last 300 years. The results of optical, radio and X-ray observations of the region up to 5 kpc around the Sun showed that there is a very small probability to find a neutron star (NS) or a SNR with such a small age.

Kaspi et al. (1999) and Kaspi & Helfand (2002) give a list of the youngest ($\tau \leq 2.44 \times 10^4$ yrs) 17 PSRs. Ten of these PSRs are genetically connected to SNRs. The opposite of this is not true, i.e. in most of the SNRs with such ages no PSR has been found. Searching for dim point X-ray sources in nearby
SNRs is essential to solve this important problem, because after finding point X-ray sources in SNRs these point sources can precisely be examined in the radio band.

Assuming the lower limit for the mass of the progenitors, which end their evolution with SN explosion, to be 5 or 8 $M_\odot$ leads to a difference of a factor of 3 in the formation rate of SNRs, if we use the initial mass function (IMF) of Blaha & Humphreys (1989). Even for different galaxies and star formation regions (SFRs) we can use a simple IMF with a value of power about 2.3–3 (Schaerer 2002). A lower limit for the mass of progenitors of SN about 7-8 $M_\odot$ is in accordance with a rate of one SN in 65 years. It is necessary also to note that the SFRs in our galaxy are not symmetrically located and also the star formation rates vary from one region to another.

## 2 Effects of the background radiation on SNR and PSR searches

### 2.1 Effects of the background radiation on each PSR and each SNR separately

It is known that the background radio radiation increases when the line of sight becomes closer to the Galactic center direction and the Galactic plane. Distribution of the temperature which characterizes the background radiation at 400 MHz is known ('Physics of Cosmos' 1986). When we compare the intensity (temperature) of the background radiation with the structure of the Galactic arms (Georgelin & Georgelin 1976; Paladini et al. 2003), the effect of giant HII regions located in SFRs is seen.

As known, the source of the background radiation in the radio band is electron gas and number density of electrons increases under the approach to the Galactic center. Mainly because of this reason, as the direction approaches to the Galactic longitude $l=0^\circ$ and the Galactic latitude $b=0^\circ$, intensity of this radiation increases. Naturally, the background radiation is most effective on the PSRs with low flux values and on the SNRs with low surface brightness ($\Sigma$) values.

In the Galaxy, there are HII region complexes (which include several OB associations) with large sizes and high surface brightness values. Some of
these complexes are located close to the Sun and in the directions far away from the Galactic center direction. Such HII region complexes can have considerable contribution to the background radio radiation and they can change the smoothness of distribution of the background radiation at small angular sizes. This is clearly seen, for example, for the region where Vela is located in (262° < l < 268°). Below, we will discuss the effect of the background radiation and the effects of different SFRs (which include many O-type stars) on the PSR search at 1400 MHz and on the SNR search at 1000 MHz. Please note that the searches for PSRs at 400 MHz have high sensitivity only in the Arecibo window (40° < l < 65°, |b|≤2.5°, Hulse & Taylor 1974, 1975). It must also be noted that PSRs have steep spectrum in general, so that, effect of the background radiation is not so important on radiation of PSRs at 400 MHz.

We have examined the effect of Galactic background radiation on the observed SNRs by considering the l and b values. SNRs G3.8+0.3 and G354.8-0.8 are the dimmest among the SNRs which are the closest to the Galactic center direction (in the range l=0°±10° and |b|<2°). Σ values of these 2 SNRs are, respectively, 1.86×10^{-21} Wm^{-2}Hz^{-1}ster^{-1} and 1.17×10^{-21} Wm^{-2}Hz^{-1}ster^{-1}. The SNRs G6.4+4.0 and G358.0+3.8 (which have a bit larger |b| values) have Σ values 2.04×10^{-22} Wm^{-2}Hz^{-1}ster^{-1} and 1.56×10^{-22} Wm^{-2}Hz^{-1}ster^{-1}, respectively. It is possible to observe such low-Σ SNRs with |l|>60°–70° (i.e. far away from the Galactic center) and even with |b|<2°. Among the observed SNRs only 2 of them (G156.2+5.7, which is not shown in Figure 1, and G182.4+4.3) have Σ < 10^{-22} Wm^{-2}Hz^{-1}ster^{-1} (Green 2001). So, the effect of the background radiation on the SNR search in the Galactic anticenter directions can surely be neglected for the SNRs with Σ ≥ 3×10^{-22} Wm^{-2}Hz^{-1}ster^{-1} (see Figures 1 and 2). On the other hand, only 21% of all the SNRs given in Green (2001) have Σ < 10^{-21} Wm^{-2}Hz^{-1}ster^{-1}. For the SNRs in the anti-center directions, even if the Σ values are small, the flux values (F≈Σ×θ², where θ is the angular diameter of the SNR) can be larger compared to the flux values of the SNRs in the Galactic central directions in most of the cases (see Figure 3), because the SNRs in the anticenter directions have, in general, smaller distances and larger sizes.

Among the known PSRs in the interval l=0°±10° and |b|<2°, PSR J1728-3733 (l = 350°.8, b = −1°.66) has the lowest flux at 1400 MHz: F_{1400} = 0.19 mJy. Other low-flux PSRs are PSR J1804-2228 (l = 7°.72, b = −0°.4) with F_{1400} = 0.2 mJy and both PSR 1736-3511 (l = 353°.6, b = −1°.6)
and PSR J1751-2516 ($l = 3°.85$, $b = 0°.69$) with $F_{1400} = 0.22$ mJy. So, the background radiation practically can not hide PSRs in the surveys of the last $\sim 10$ years if $F_{1400} > 0.2$ mJy (similar to the case of SNRs with $\Sigma > 10^{-21}$ Wm$^{-2}$Hz$^{-1}$ster$^{-1}$) (Figures 4,5). It is necessary to note that the observations of PSRs also depend on the pulse period, the dispersion measure and also the observational instruments. Here it is easier and more reliable to make statistical investigations because most of the PSRs were observed with the same telescope. Below, we will examine the influence of the background radiation and the influence of nearby HII regions on PSR and SNR searches.

2.2 Effect of the background radiation on the samples of PSRs and SNRs

We can assume that, the SNR search in the Galaxy has been made with roughly the same sensitivity, but not necessarily with the same precision, in all directions. In Figure 3, flux values (at 1000 MHz) of the SNRs (Green 2001) with respect to Galactic longitude for the SNRs with $|b| < 5^\circ$ are represented. As seen in this figure, the SNRs were searched down to the same flux value in all directions, but, since SNRs are extended objects, the SNRs with larger angular sizes are more easily observed in the Galactic anticenter directions. Observing SNRs depends significantly on their $\Sigma$ values as well as their fluxes.

The distribution of the SNRs in different longitude intervals with respect to $\Sigma$ show that the longitude interval which is the most affected by the background radiation is $l = 0^\circ \pm 40^\circ$ (Figure 2). How this effect decreases as the line of sight recedes from the Galactic center direction is also clearly seen. As mentioned above, among the SNRs with $|b| < 5^\circ$ the lowest $\Sigma$ value belongs to SNR G182.4+4.3. As seen from Figure 1, in the Galactic central directions, except $l \cong 0^\circ \pm 40^\circ$, almost all the SNRs with $\Sigma > 3 \times 10^{-22}$ Wm$^{-2}$Hz$^{-1}$ster$^{-1}$ are observable. The background radiation is strong in the regions $l \cong 10^\circ - 30^\circ$ and $l \cong 330^\circ - 340^\circ$, and the number of the HII regions in these intervals is large (’Physics of Cosmos’ 1986; Georgelin & Georgelin 1976; Paladini et al. 2003). Since this is related to the number of massive stars being large in these intervals, this fact shows itself in Figure 1. In such regions the formation rates of SNRs and PSRs must be high. The result of this is not clearly seen in Figures 1–3, but it can be seen in Figures 4 and 5 which show
the distributions of the PSR sample including young PSRs. In these regions also, number of the SNRs with high surface brightness values is large.

In the last 7 years, the Galactic plane (especially the southern hemisphere) and particularly the Galactic central directions were observed at 1400 MHz and a large number of new PSRs were found (Johnston et al. 1995; Manchester et al. 1996; Sandhu et al. 1997; Lyne et al. 1998, 2000; Camilo et al. 2001; Edwards & Bailes 2001a,b; Manchester 2001, D’Amico et al. 2001; Manchester et al. 2002; Morris et al. 2002). As a result of these searches, today the number of the known PSRs with measured 1400 MHz flux is larger than the number of the known PSRs with measured 400 MHz flux. Because of this, we examine the PSRs observed at 1400 MHz.

In Figure 4, 634 PSRs with \(|b| < 5^\circ\) are displayed. As seen from the flux distribution with respect to the Galactic longitude, many PSRs with small \(F_{1400}\) values are located in Galactic arms and in the Galactic central directions. From the figure it is seen that, in the \(280^\circ < l < 340^\circ\) part of the region which was searched with the highest sensitivity (\(F_{1400} < 0.2\) mJy) more low-flux PSRs were found. In the interval \(l = 0^\circ\pm20^\circ\) the number of PSRs with \(F_{1400} < 0.2\) mJy is very small. The reason for this is not the search being not so sensitive and precise, but the background radiation being very strong. In Figure 5, \(F_{1400} - l\) diagram of 496 PSRs with \(|b| < 2^\circ\) is displayed. When we compare Figures 4 and 5, we see a larger decrease in the number of the PSRs located in the Galactic central directions which have \(F_{1400} < 0.2\) mJy.

In Figure 6, \(|z| - l\) diagram of the PSRs with \(|l| < 70^\circ, |b| < 2^\circ, DM < 800\) pc/cm\(^3\) and \(F_{1400} < 0.5\) mJy is represented. Since the electron density strongly depends on the longitude value, as the direction becomes far away from the Galactic center direction, the PSRs (in such directions) which have the same DM value that the PSRs in the Galactic center direction have, are located at larger distances. This leads to the possibility of the \(|z|\) values to be larger for the same \(|b|\) values. For the same DM value of two different PSRs, the smaller distance value belongs to the one which is closer to the Galactic center direction. As seen from Figure 8, although the distances of the PSRs in the interval \(l = 0^\circ\pm20^\circ\) are somewhat less, the average \(|z|\) value is larger and this shows that the average \(|b|\) value of these PSRs is larger. This is also a result of the effect of the background radiation.

In order to have the probability of observing the PSRs with roughly the same flux values and the SNRs with roughly the same \(\Sigma\) values to be almost
the same for the whole Galactic plane and in order not to reduce the number of the objects too much, we will first consider only the PSRs with $F_{1400} \geq 0.2$ mJy and the SNRs with $\Sigma$ (at 1 GHz) $\geq 10^{-21} \text{Wm}^{-2}\text{Hz}^{-1}\text{sr}^{-1}$.

The character of the background radiation (see Figure 1) does not show the possibility of the influence of each of the OB associations separately on observations of PSRs and SNRs. Despite this fact, we have checked the possibility of influences of the OB associations given in the lists of Garmany & Stencel (1992) and Melnik & Efremov (1995). We did not find any significant contribution of any one of the OB associations to the Galactic background radiation.

3 Discussion and Conclusions

Observational data of PSRs (ATNF Pulsar Catalogue 2003; Guseinov et al. 2003a) and SNRs (Green 2001) show that even in the Galactic central directions ($l=0^\circ \pm 60^\circ$, $|b|<2^\circ$) all the SNRs with $\Sigma>10^{-21} \text{Wm}^{-2}\text{Hz}^{-1}\text{sr}^{-1}$ and the PSRs with $F_{1400}>0.2$ mJy are observable. Since the background radiation is strongly dependent on the Galactic latitude, the SNRs with $\Sigma>1.5\times10^{-22} \text{Wm}^{-2}\text{Hz}^{-1}\text{sr}^{-1}$ in the same longitude interval can be observed if $|b|>4^\circ$. Also, the SNRs in the interval $60^\circ < l < 300^\circ$ can easily be observed for all values of $b$ if $\Sigma>3\times10^{-22} \text{Wm}^{-2}\text{Hz}^{-1}\text{sr}^{-1}$.

In the Galaxy, total number of the SNRs with $\Sigma>3\times10^{-22} \text{Wm}^{-2}\text{Hz}^{-1}\text{sr}^{-1}$ and $d<3.2$ kpc in the interval $60^\circ < l < 300^\circ$ is 33 (Guseinov et al. 2003b). It is seen from PSR-SNR associations that the ages of the SNRs which are genetically connected to PSRs do not exceed $3\times10^4$ yr in general (Kaspi & Helfand 2002). Since the SNRs in the regions we examined have less surface brightness values on average, we can roughly say that the ages of these SNRs may exceed $3\times10^4$ yr but not greater than $5\times10^4$ yr. There are 23 SNRs with $\Sigma>10^{-21} \text{Wm}^{-2}\text{Hz}^{-1}\text{sr}^{-1}$ located at $d\leq3.2$ kpc from the Sun, among which 14 of them are in the sector under consideration. If we assume that the ratio of the number of the SNRs with $3\times10^{-22} < \Sigma \leq 10^{-21} \text{Wm}^{-2}\text{Hz}^{-1}\text{sr}^{-1}$ to the number of the bright SNRs in the central region ($l=0^\circ \pm 60^\circ$) is equal to the same ratio of the SNRs in the region $60^\circ < l < 300^\circ$, then we can use the ratio for the Galactic anticenter directions to find the number of dim SNRs in the Galactic central directions. In this case, the number of the SNRs with $\Sigma>3\times10^{-22} \text{Wm}^{-2}\text{Hz}^{-1}\text{sr}^{-1}$ and ages $\leq5\times10^4$ yr in the region up to 3.2 kpc
from the Sun is 54. If we further assume that the radius of the Galaxy is 12 kpc and the average number density of the SNRs in the whole Galaxy is the same as the number density of the SNRs within 3 kpc around the Sun, then the number of the SNRs having ages less than $5 \times 10^4$ yr must be about 800 in the Galaxy. (Since the distribution of SNRs in the Galaxy is not homogeneous and the distribution of their number density with respect to Galactic radius is not known well, we can not estimate number of the SNRs considerably better). From this result, the formation rate of SNRs turns out to be about one in 65 yr which is approximately the same as the SN explosion rate (van den Bergh & Tammann 1991; Capellaro et al. 1999; Capellaro & Turatto 2001). We can use the same approach to estimate the birth rate of PSRs.

There are 48 PSRs with $\tau \leq 10^6$ yr located at $d \leq 3.2$ kpc around the Sun (Guseinov et al. 2003a). If we assume the distribution of the PSRs in the Galaxy to be similar to the distribution of the SNRs given above, then the number of PSRs with $\tau \leq 10^6$ yr must be about 710 in the Galaxy. If we further assume the beaming factor to be $\sim 0.35$ (Lyne & Graham-Smith 1998), then number of the PSRs turns out to be 2030. We can estimate the total number of PSRs knowing that 75% of the PSRs around the Sun have $L_{1400} > 3$ mJy kpc$^2$ and using the luminosity function of Guseinov et al. (2003c): the number of PSRs with $\tau \leq 10^6$ yr must be $\sim 4.5 \times 10^3$ in the Galaxy. Using this result the birth rate of PSRs is found to be one in 220 yr. But the PSRs with magnetic fields $> 10^{13}$ G may pass the death belt in less than $10^6$ yr. Taking this fact also into account, the birth rate of PSRs can roughly be assumed to be one in 200 yr. If we have used the luminosity function of Lorimer et al. (1993) or Allakhverdiev et al. (1997) instead of the luminosity function given by Guseinov et al. (2003c), then the birth rate of PSRs would be a bit larger.
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Figure 1: Surface brightness versus longitude diagram for 201 SNRs with $|b|<5^\circ$. 
Figure 2: Surface brightness versus longitude diagram for 171 SNRs with $|b|<2^\circ$. 
Figure 3: $F_{1000}$ versus longitude diagram for 197 SNRs with $|b|<5^\circ$. 
Figure 4: $F_{1400}$ versus longitude diagram for 634 PSRs with $|b|<5^\circ$. 
Figure 5: $F_{1400}$ versus longitude diagram for 496 PSRs with $|b|<2^\circ$. 
Figure 6: $|z|$ versus longitude diagram of PSRs with $|b|<2^\circ$, $F_{1400}<0.5$ mJy, $-70^\circ<l<55^\circ$ and DM$<800$ pc/cm$^3$. 