RADIO SPECTRA OF COMPLETE SAMPLE OF GALACTIC SUPERNOVA REMNANT

S.A. Trushkin

Special astrophysical observatory
Nizhnij Arkhyz, 357147, Russia *satr@sao.ru*

ABSTRACT. We present radio continuum spectra for 192 Galactic supernova remnants (SNRs) from 220 known and included in Green's (1998) catalog. These spectra include most of measurements available in literature, as well as multi-frequency measurements of nearly 120 SNRs with the RATAN-600 radio telescope.

The measurements have been placed on the same absolute flux density scale of Baars (1977). The presented compilation has given a possibility of plotting quite accurate spectra accounting for the thermal plasma free–free absorption in fitting the spectra accounted for.

From 190 spectra seventy eight (41%) have clear frequency turnover caused, apparently, by absorption in the thermal foreground within Milky Way. Frequencies of ($\nu_{\tau=1}$) are distributed from 5 to 365 MHz, with medium value : 32 MHz.

There are no correlations between Galactic coordinates, spectral index and $\nu_{\tau=1}$ in the sample of SNRs, but there is significant correlation of the frequency $\nu_{\tau=1}$ and distances, estimated from $\Sigma - D$ relation.

Key words: ISM: supernova remnants; radio continuum: ISM

1. Introduction

The non-thermal radio spectrum is a key property distinguishing SNRs from extended Galactic plane radio sources. The current catalog of SNRs (Green, 1998) contains 220 Galactic SNRs and some dozens of possible or probable ones, named SNR candidates here. While it contains information about the spectral index and flux densities at 1 GHz, there is no complete collection of the available data on flux density measurements, scattered over hundreds of publications and catalogs. Reviews of radio spectra of a few dozen SNRs are given in many early papers and the recent papers by Kassim (1989a,b), Kovalenko et al. (1994a, 1994b) and the papers on Galactic plane sources (Reich et al., 1988) based on the 11 cm and 21 cm Effelsberg Galactic plane surveys (Reich et al., 1990a, 1990b).

The results of new all-sky surveys with a resolution of about 1′ are presently available, which comprise much more data on extended sources in the Galactic plane.

We used our measurements of the flux densities of nearly 120 SNRs (Trushkin, 1986, 1996ab, 1997; Trushkin et al., 1988). Thus the flux densities of half of the SNRs were measured at several (up to six) frequencies, which corrected and complemented essentially the spectra of many SNRs.

We collected all these data and make them accessible in the CATS database (Verkhodanov et al., 1997). The spectrum plotting procedure of the SNRs with optional fitting is designed to simplify the statistical investigation of radio properties of these SNRs by providing easy and public access to the available data.

While there are no significant correlations of global SNR parameters with the spectral indices (Caswell and Clark, 1975; Lerche, 1980), Weiler (1983) proposed an extremely important classification which divided the SNRs into groups: shells, plerions, and composite SNRs. Probably the SNRs are intimately related with the basic type classification of supernova: SNIa, SNIb and SNII. The SNIb and SNII are the birthplace of neutron stars and black holes and thus lead to production of plerions or, in dense ISM, composite SNRs with appearance of filled-center and shell structure in the X-rays and radio emission, respectively. On the other hand, the classical shells are created by SNIa, as is the case with the historical SN 1604 Tycho. Besides the morphology differences in radio emission, these three classes of SNRs have different mean spectral indices ($S_\nu \propto \nu^\alpha$) (Weiler, 1983, 1985).

Accurate spectra are very important for the classification "shell/plerion", recognition of the mechanism of generation of relativistic particles, search for possible high- or low-frequency turnovers of spectra. The theoretical calculations of evolution of radio spectra and possible correlation between spectral index and surface brightness ("$\Sigma - D$", "$\alpha - \Sigma$" planes) should be confirm by observational data of the total samples to draw conclusions concerning the physical evolution of SNRs.

2. Flux density measurement data

The catalog of the flux measurements contains nearly 2300 entries, which is a base for plotting the spectra of 200 SNRs and candidates. We have used our measurements of the flux densities of about 120 SNRs (Trushkin, 1986, 1996a,b, 1997; Trushkin et al., 1988). We added to the list of SNRs four first detected SNRs: G3.2−5.2, G11.2−1.1, G16.2−2.7, G16.0+2.7 and G356.2+4.4, and also the SNR candidates G4.7+1.3, G4.8+1.2, G4.8+6.2, G9.7−0.1 and G85.2−1.2 from Duncan et al. (1997). Detailed paper about G16.2-2.7 have been submitted by the author in A&A in 1999. The complete list of RATAN-600 data contains 350 multi-frequency measurements.

The thermal absorption of the foreground describes well the spectra of most SNRs:

$$S_\nu = [S_{408}(\nu/408)^\alpha]\ \mathtt{exp}[-\tau_{408}(\nu/408)^{-2.01}].$$

Kassim (1989b) used the low-frequency data to derive spectra for 32 SNRs, and their turnovers at low frequencies (< 100 MHz) to indicate the presence of extended ionized medium along the line of sight.

For fitting we used, as a rule, an approximation formula, $y = A + Bx + C\,\mathtt{exp}(Dx)$, or a simple linear case, $y = A + Bx$, where $x = \log\nu$, $y = \log S_\nu$, ν — frequency (MHz), S_ν — flux density (Jy), $D = \pm 1$ or $D = -4.83$. Clearly the latter case is adequate to real thermal absorption at low frequencies and steady in fitting the spectra with a few points. The inverse squares of relative flux errors, $(\Delta S_\nu/S_\nu)^{-2}$, are used as formal weights of their flux points. Often we used the option "without errors" for the spectrum plotting, when the scattering of points of spectrum is larger than the values of errors.

For fitting the curve we give two spectral indices at 0.4 and 4 GHz if these frequencies are within the fitting range. The first one is closer to $\tau = 1$ since the spectra have maxima near 10–100 MHz, while $\nu_{max} \simeq 3\,\nu_{\tau=1}$. The second one is the spectral index of an optically thin spectrum and is not influenced by propagation conditions, but there is a high-frequency turnover of spectra because of the properties of synchrotron radiation.

Trushkin (1998) presented atlas of spectra of 200 SNRs: 192 SNRs, included in Green's catalog and the spectra of eight new SNRs or SNR candidates.

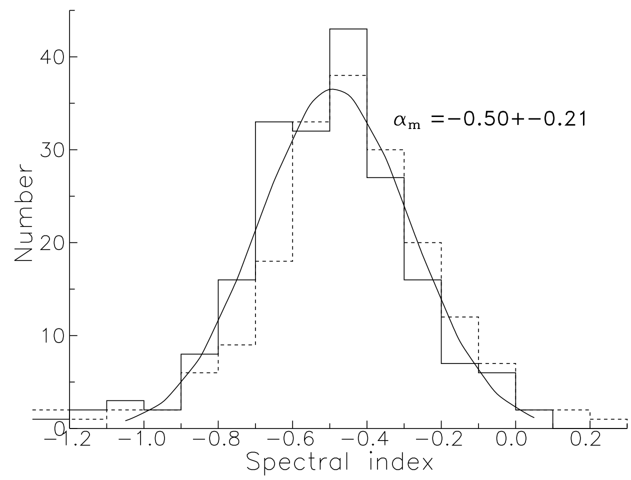

Figure 1: Distribution of α_4 (solid line) and $\alpha_{0.4}$ (dashed line) for 192 SNRs

As Lerche (1980) has shown, Bell's (1978a,b) mechanism (as a variant of the Fermi acceleration of the first order) of repowering is attractive because it provides a simple explanation of the observed spread of spectral indices: from acceleration whether on a strong adiabatic shock wave with a compression factor $\chi = 4$ or on a strong isothermal shock with $\chi = 2.4$. Thus the spectral index of relativistic electrons, $\gamma = \frac{2+\chi}{\chi-1}$, varies from 2 to 3.1. Therefore the spectral indices may vary from −0.5 to −1.1 if the equation of state in SNR is described by strong adiabatic or isothermal shocks.

An analysis of 190 spectra showed that 78 SNRs (41 %) have clear low-frequency turnover caused, apparently, by absorption in the thermal foreground of the Milky Way. Fig. 7 shows the distribution of the turnover frequency ($\tau = 1$) for these SNRs.

These frequencies $\nu_{\tau=1}$ do not correlate with the Galactic coordinates, while $\nu_{\tau=1}$ in Anticenter direction are below than in Galactic Center direction. In Fig.5 and Fig.6 $\nu_{\tau=1} - l$ and $\nu_{\tau=1} - n$ are given. Thus most SNRs have frequency of turnover ($\nu_{\tau=1}$) below 80 MHz. We could search for considerable correlation between a turnover frequency and distance of SNRs. Because the distance d estimates for individual SNRs are very uncertain, d we could only use $\Sigma - D$ relation for estimate of distances to SNRs. A new refined $\Sigma - D$ relation was obtained by Case & Bhattachatya (1998) for a sample of 36 Galactic shell SNRs: $\Sigma_{1\mathrm{GHz}}(\mathrm{W\,Hz^{-1}m^{-2}sr^{-1}}) = 2.07^{+3.10}_{-1.24} \times 10^{-17} D_{\mathrm{pc}}^{-2.38\pm0.26}$. They also give table for all SNRs from Green's catalog, where the size and flux density at 1 GHz could be estimated.

From 16 SNRs with active neutron stars (Frail, 1998), the spectra of 15 ones have no low-frequency turnover at $> 20-50$ MHz which is logically associated with the contribution of neutron stars (or pulsars) inside SNRs. Pulsars as a rule have steeper spectra than

3. Analysis of spectra

The sample mean spectral indices at 0.4 and 4.0 GHz are $\alpha_{0.4} = -0.45 \pm 0.2$ and $\alpha_4 = -0.50 \pm 0.21$. The distributions of the low- and high-frequency spectral indices ($\alpha_{0.4}$ and α_4, respectively) for 192 SNRs are shown in Fig. 1. For comparison we present the best gaussian fit of the distribution with a dispersion $\sigma = 0.3$. There is no significant difference in the distributions of both spectral indices.

Spectral index do not correlate with the Galactic coordinates. In Fig.2 and Fig.3 $\alpha - l$ and $\alpha - b$ dependences are given.

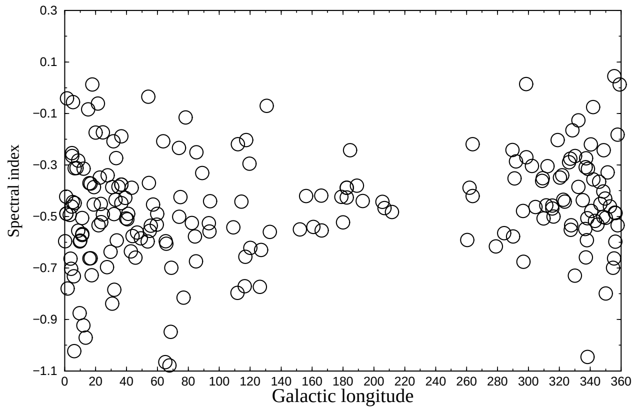

Figure 2: The spectral index via Galactic longitude.

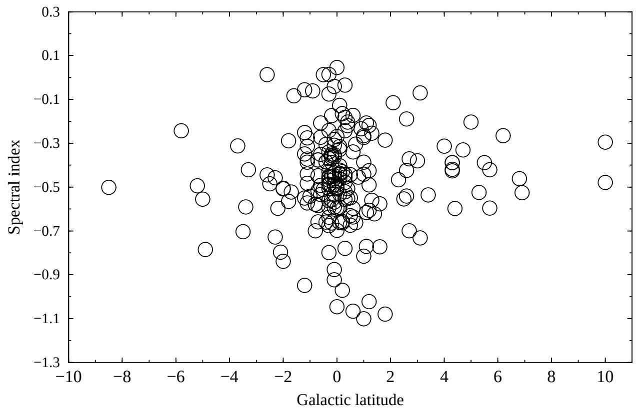

Figure 3: The spectral index via Galactic latitude.

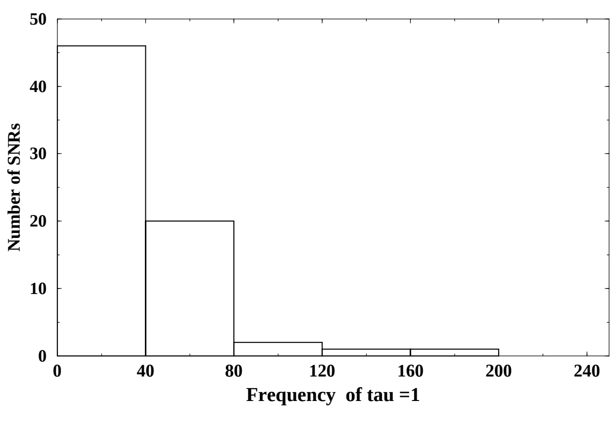

Figure 4: Distribution of turnover frequency ($\tau = 1$) for 78 SNRs

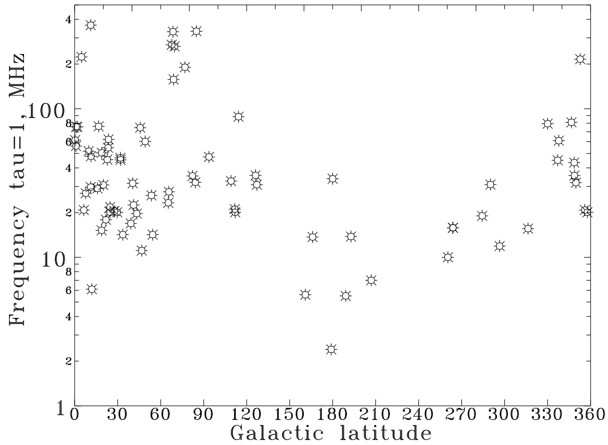

Figure 5: Frequency of turnover ($\tau = 1$) via Galactic longitude (78 SNRs)

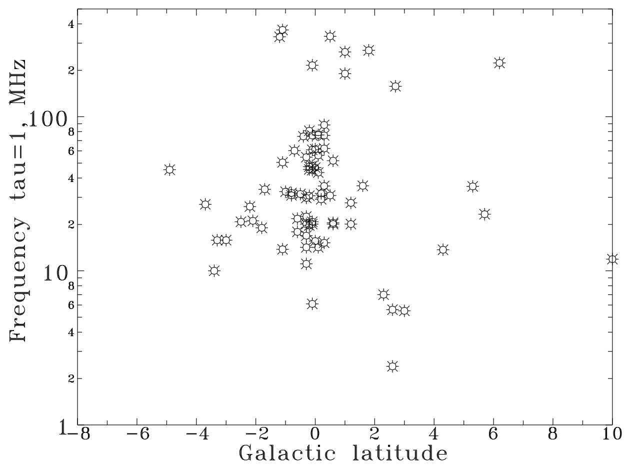

Figure 6: Frequency of turnover ($\tau = 1$) via Galactic latitude (78 SNRs)

SNRs, thus their contribution will be higher at low frequencies.

The catalog of SNR spectra has ten cases of clear turn-up at low frequencies. It is interesting that five (50 %!) such SNRs contain radio pulsars (Kaspi, 1998). Of course, it is probable that there is discrepancy of flux scales in low- and high-frequency measurements of flux densities. But in further observations we should pay special attention to the sample of SNRs without turnover or even with turn-up at low frequencies for search for pulsars or active stellar supernova remnants. There is significant correlation of the frequency $\nu_{\tau=1}$ and distances, estimated from $\Sigma - D$ relation ($\rho = 0.61 \pm 0.05$). It could be easily explained by either increasing the probability to catch at line of sight the absorbing HII region or increasing of the path in absorbing interstellar medium.

There are few data for SNR with large angular size at frequencies higher than 10 GHz in our catalog. Only

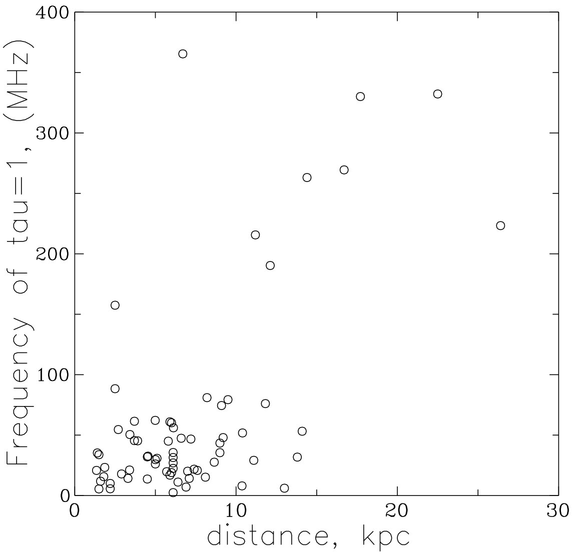

Figure 7: Turnover frequency ($\tau = 1$) for 70 SNRs via estimated distance $d_{\Sigma-d}$.

in these SNRs with big ages such turnovers are due to synchrotron losses. Thus the high-frequency surveys of the SNRs are needed.

4. Conclusions

We present radio continuum spectra for 192 Galactic supernova remnants (SNRs) from 220 known and included in Green's (1998) catalog. We added eight SNR candidates detected in the Galactic survey carried out with the RATAN-600 radio telescope (Trushkin, 1996) and in the investigations of 1997–1998. The catalog contains about 2200 flux density measurements. The spectra can be plotted only for 200 SNRs because about 20 other new and weak SNRs (Whiteoak and Green, 1996; Gray, 1994) have only one–frequency flux density measurements.

The procedure of spectrum plotting based on this catalog is "on-line" in the CATS data base *http://cats.sao.ru/C* (Verkhodanov et al., 1997).

These spectra include most flux density measurements from literature and our measurements of flux densities of nearly 120 SNRs with the RATAN-600 radio telescope in 1, 2, and 4 Galactic quadrants and from the Galactic plane survey at 0.96 and 3.9 GHz (Trushkin 1988, 1996).

Where it was possible, the flux measurements were reduced to the common flux scale of Baars (1977), as it was done in the work of Kassim (1989a). The correcting coefficients from the compiled catalog of Kuhr et al. (1981) were used.

The presented compiled catalog of flux density measurements enables one to plot spectra of SNRs with allowance made for their turnover at low frequencies due to thermal absorption in the Galaxy.

Acknowledgements. The author is grateful to his colleagues O.V. Verkhodanov, V.N. Chernenkov and H. Andernach who created the CATS database and to the Russian Foundation for Basic Research for financial support of the CATS project (grant No 96-07-89075).

References

Baars J.W.M., Genzel R., Pauliny-Toth I.I.K., et. al.: 1977, *As. A.p*, **61**, 99.

Bell A.R.: 1978a, *M.N.R.A.S.*, **182**, 147.

Bell A.R.: 1978b, *M.N.R.A.S.*, **182**, 443.

Case, G. L., Bhattacharya, D., 1998, ApJ, 504, 761

Clark D.H., Caswell J.L.: 1976, *M.N.R.A.S.*, **174**, 267.

Duncan A.R., Stewart R.T., Haynes R.F., Jones K.L.: 1997, *M.N.R.A.S.*, **287**, 722.

Gray A.D.: 1994, *M.N.R.A.S.*, **270**, 847.

Green D.A.: 1998, A Catalogue of Galactic Supernova Remnants (*1998 Sept. vers.*), MRAO, UK (available on the WWW at "http://www.mrao.cam.ac.uk/surveys/snrs/").

Kaspi V.M.: 1998, Adv. in Space Research, **21**, 167.

Kassim N.E.: 1989a, *Ap.J.*, **347**, 915.

Kassim N.E.: 1989b, *Ap. J. S.*, **71**, 799.

Kassim N.E.: 1992, *A. J.*, **103**, 943.

Kovalenko A.V., Pynzar' A.V., Udal'tsov V.A.: 1994, *A.R.*, **38**, 95.

Kovalenko A.V., Pynzar' A.V., Udal'tsov V.A.: 1994, *A.R.*, **38**, 110.

Kuhr H., Witzel A., Pauliny-Toth I.I.K., Nauber U.: 1981, *As. Ap. S.*, **45**, 367.

Lerche I.: 1980, *A. & A.*, **85**, 141.

Reich W., Fürst E., Reich P., Reif K.: 1990a, *As. Ap. Suppl.*, **85**, 633.

Reich W., Fürst E., Reich P., Junkes N.: 1988, in: "Supernova remnants and the Interstellar Medium", *IAU*

Colloquium N **101**, eds.: Roger R.S & Landecker T.L. Cambridge University Press, 293.

Reich W., Reich P., Fürst E.: 1990b, *As.Ap.Suppl.*, **83**, 539.

Trushkin S.A.: 1986, *Astron. Tsirk.*, **1453**, 4.

Trushkin S.A.: Vitkovskij V.V., Nizhelskij N.A., 1988, Astrofiz. Issled. (Izv. SAO), **25**, 84.

Trushkin S.A.: 1996a, *Bull. SAO*, **41**, 64.

Trushkin S.A.: 1996b, Astron. Astrophys. Trans., **11**, 225.

Trushkin S.A.: 1998, *Bull. SAO*, **46**, 65.

Verkhodanov O.V., Trushkin S.A., Andernach H., Chernenkov V.N.: 1997, *in: "Astronomical Data Analysis Software Systems VI"*, eds.: G.Hunt & H.E.Payne., *ASP Conference Series*, **125**, 322.

Whiteoak J.B.Z., Green A.: 1992, *A.& A. S.*, **118**, 329.

Weiler K.W.: 1983, *Observatory*, **1054**, 85.

Weiler K.W.: 1985, *in: "Crab Nebula and related supernova remnants"*, eds.: M.C. Kafatos & R.B.C. Henry, Cambridge Un. Press., 227.