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ESTIMATION OF BRIGHTNESSES AND SPECTRAL INDICES OF RADIO LOOPS

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Abstract. We present a method for determination of brightnesses and spectral indices of radio-continuum loops which was developed for large Galactic radio loops and test if it is also applicable for angularly extended supernova remnants (SNRs). In this method, we use contours and profiles of the brightness temperatures for each loop. The measurements at more frequencies are used. Also, we shown reality of Loops V and VI. We calculated the mean brightness temperatures and surface brightnesses of the six main Galactic radio-continuum loops I-VI at the four frequencies: 1420, 820, 408 and 22 MHz. For evolved SNRs, Monoceros, Cygnus and HB 21, we used some of these frequencies: 2720, 1420, 820, 408, 34.5 and 22 MHz. For calculating radio spectral indices, we used the spectra (mean brightness temperature versus frequency) between several frequencies, or $T-T$ graphs method. For radio-continuum loops I-VI, Monoceros and Cygnus the results confirm their non-thermal origin. For HB 21 we found both components, thermal and non-thermal. Besides, the obtained results also show that our method which was developed for large radio loops is applicable to the SNRs, as well.

1. INTRODUCTION

We studied the brightness temperatures, surface brightnesses and spectra of the radio-continuum loops. Radio loops consist of more spurs lying approximately in the same small circle of the celestial sphere. The objects of study were six main Galactic radio loops: Loops I-IV at the frequencies 1420, 820, 408 and 22 MHz, Loops V and VI at 1420, 820 and 408 MHz, and three SNRs. These smaller loops are: Monoceros, listed in Green's Catalogue of Galactic SNRs (Green 2009a,b) as G205.5+0.5, at the three frequencies 1420, 820 and 408 MHz, Cygnus (G74.0-8.5) at the five frequencies 2720, 1420, 820, 408 and 34.5 MHz and HB 21 (G89.0+4.7) at 1420, 820, 408, 34.5 and 22 MHz.

The main motivation of this research was investigation of the origin of radio loops and the nature of their emission (is that emission of thermal or non-thermal origin). We also wanted to confirm the reality of Loops V and VI.

2. DATA AND METHOD

We used observational data, i.e. digital surveys of the sky which are available at the site of Max-Planck-Institut für Radioastronomie in Bonn, Germany: http://www.mpifr-bonn.mpg.de/survey.html. These surveys are obtained from the continuum-radio emission. The used surveys are the following: 2720 MHz (Reif et al. 1987), 1420 MHz (Reich & Reich 1986), 820 MHz (Berkhuijsen 1972), 408 MHz (Haslam et al. 1982), 34.5 MHz (Dwarakanath & Udaya Shankar 1990) and 22 MHz (Roger et al. 1999). Their angular resolutions are $0^\circ.35$, $0^\circ.59$, $1^\circ.2$, $0^\circ.85$, $0^\circ.7$ and $1^\circ.7$, respectively. The corresponding observations are given at the following rates (measured data) for both l and b: $\frac{1^\circ}{8}$ at 2720 MHz, $\frac{1^\circ}{4}$ at 1420 MHz, $\frac{1^\circ}{2}$ at 820 MHz, $\frac{1^\circ}{3}$ at 408 MHz, $\frac{1^\circ}{5}$ at 34.5 MHz and $\frac{1^\circ}{4}$ at 22 MHz.

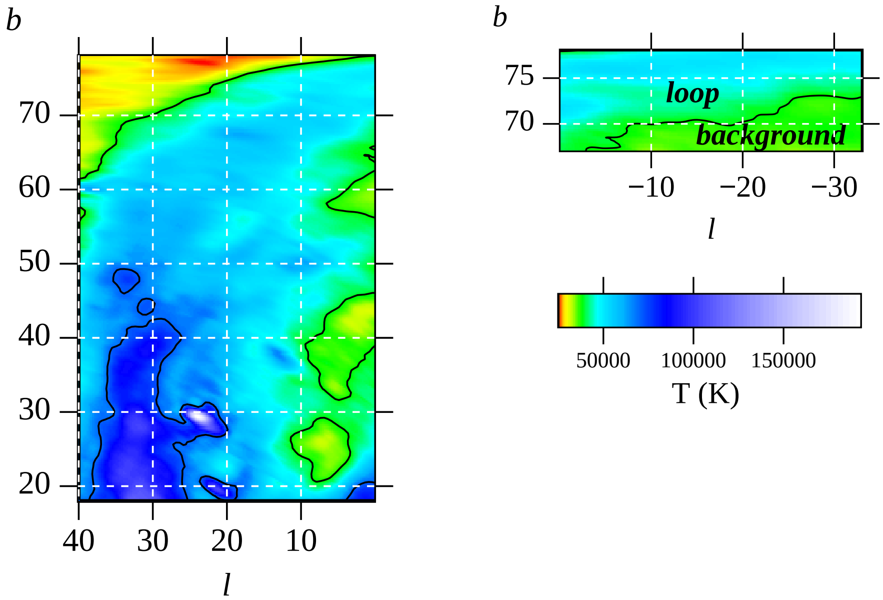

Figure 1: North Polar Spur (NPS) of the Loop I at 22 MHz, with contours $T_{\min} =$ 38000 K and $T_{\max} = 70000$ K (left: NPS part which is normal to the Galactic plain, right: NPS part which is parallel to the Galactic plain). This figure is obtained from data and represents visual illustration for brightness temperature contours method.

The average brightness temperatures of the loop at these frequencies were estimated from the radio-continuum survey data. For each loop, the area was divided into different sections (corresponding to its spurs) and estimates for these sections were combined. Background radiation was subtracted in this way: first the temperature of the loop appended with the background was determined and then the temperature of surrounding only - near the loop. After that we calculated the difference between these values and these are average temperatures. The method of calculation is described in Borka (2007) for Galactic radio loops I-VI, Borka, Milogradov-Turin & Urošević (2008) for Loops V and VI, Borka Jovanović & Urošević (2009a) for Monoceros loop, Borka Jovanović & Urošević (2011) for Cygnus and in Borka, Borka Jovanović &

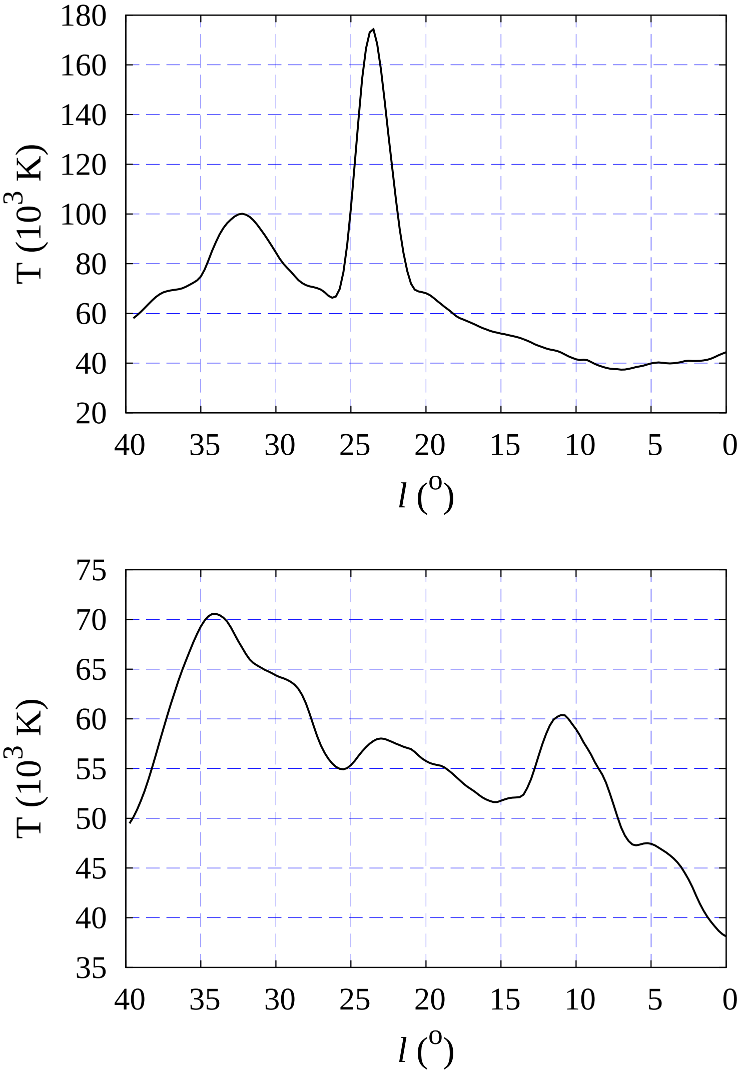

Figure 2: The temperature profiles for NPS at 22 MHz, for Galactic longitude range from $l = 40°$ to $0°$ and for Galactic latitude $b = 29°$ (top) and $b = 49°.25$ (bottom).

Urošević (2011) for HB 21. With estimated brightness temperatures ($T_{\rm b}$), we can calculate surface brightnesses.

We developed method which is easier for using than the previous methods. Our method is applied in three ways with aim to check if our results are good:

- *Brightness temperature contours (isolines* $T_{\rm b}$*)*: among all the contours, the most important are the outer and inner contour which represent the loop borders. The outer one (which corresponds to $T_{\rm min}$) separates loop and background, while the inner one (which corresponds to $T_{\rm max}$) separates loop and some superposed

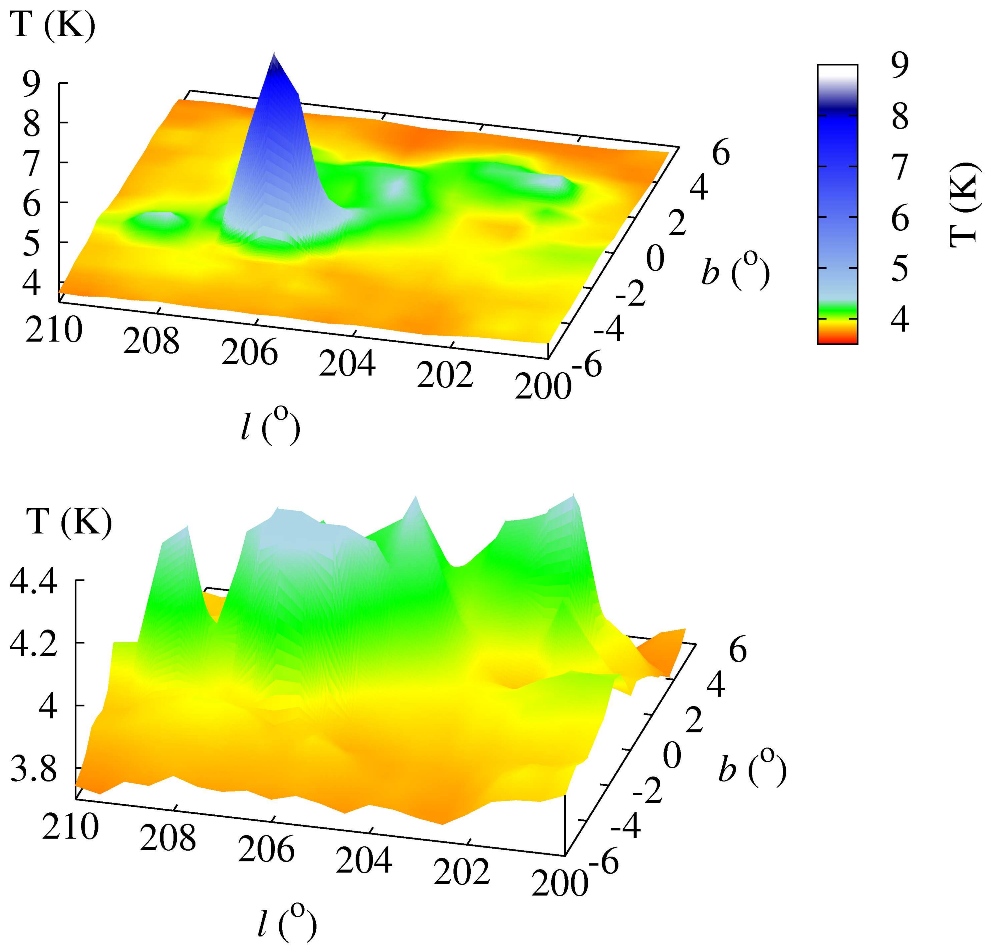

Figure 3: (*top*): An example for 3D profiles method: Monoceros SNR at 1420 MHz with temperature colorbar: $T_{\rm min}$ = 3.8 K, $T_{\rm max}$ = 4.2 K. From this 3D plot it is obvious that there is great influence of background radiation and superposed external sources, such as Rosette Nebula. (*bottom*): Area of Monoceros SNR at 1420 MHz with part of the superposed source below 4.4 K.

source. The area of the loop would be area between these two contours (see Fig. 1 for illustration).

- *Temperature profiles*: we draw profile at some Galactic latitude, in the given range of Galactic longitudes (see example in Fig. 2). From temperature profiles we can also read $T_{\rm min}$ and $T_{\rm max}$.

- *3D profiles*: using this method we can also estimate the area of the loop, if there is some superposed source, or what is the border between loop and the background (see example in Fig. 3).

Table 1: Spectral indices of radio loops (summarized from papers: Borka (2007), Borka Jovanović & Urošević (2009a), Borka Jovanović & Urošević (2011), Borka, Borka Jovanović & Urošević (2011))

loop	β
Loop I	2.74 ± 0.08
Loop II	2.88 ± 0.03
Loop III	2.68 ± 0.06
Loop IV	2.90 ± 0.28
Loop V	3.03 ± 0.15
Loop VI	2.90 ± 0.09
Monoceros	2.66 ± 0.20
Cygnus	2.66 ± 0.09
HB 21 (all frequencies)	2.45 ± 0.07
HB 21 (low frequencies)	1.01

This method we developed for large radio loops (I-VI), but later on we applied it to much smaller loops (Monoceros, Cygnus and HB 21) and showed that it is rather efficient in the case of smaller radio loops.

3. RESULTS AND CONCLUSIONS

We investigated Loops I-VI in papers Borka, Milogradov-Turin & Urošević (2006), Borka (2006), Borka (2007), Borka, Milogradov-Turin & Urošević (2008), Borka Jovanović & Urošević (2010), Urošević & Borka Jovanović (2011). Smaller remnants we investigated in papers Borka Jovanović & Urošević (2008), Borka Jovanović & Urošević (2009a,b), Borka Jovanović & Urošević (2010), Borka Jovanović & Urošević (2011), Borka, Borka Jovanović & Urošević (2011). For all of these loops we determined spectra. These are graphs: temperature versus frequency. From these spectra we obtained radio spectral indices. From the radio spectral index β (see Table 1) we can estimate the origin of radiation (thermal or non-thermal). It can be noticed that all spectral indices are greater than 2.2 which means that radiation is non-thermal. In case of HB 21 remnant, we noticed flatter spectral indices at frequencies below 408 MHz as it was proposed by Leahy (2006). Our analysis of HB 21 indicates that the spectrum of HB 21 is a combination of synchrotron and thermal components.

For Loops V and VI and for smaller loops, besides spectra, we obtained temperature-temperature plots. It can be noticed that values for β agree well with the corresponding values obtained from spectrum, as expected (see Uyaniker et al. 2004).

Our main result is that we gave a new method for determining position and calculating average brightness temperature and surface brightness of the radio loops. Results from our method agree very well with results obtained by other independent methods.

We showed that method for defining a loop border and for determining the values of temperature and brightness, which we developed for main Galactic loops I-VI, could be applicable to all SNRs.

We can conclude that:

- The method which we developed enabled estimations of the brightness of the Loops I-VI, Mon, Cyg, HB 21.
- The method shown is easier to use than the previous methods.
- We estimated the brightness temperatures and surface brightnesses of these loops at the three (and somewhere five) frequencies.
- We have demonstrated the probable existence of Loops V and VI: they display shell structure and have non-thermal spectra, similar to the main loops I-IV which are usually assumed to be SNRs.
- With new derived brightnesses, using $\Sigma - D$ relations for SNRs, we derived diameters and distances to the Loops I-VI at the three frequencies and then estimated some average distance. The estimated distances of the main radio loops are in good agreement with the earlier results. We also estimated distance to Monoceros loop.
- We find that good linear fits can be made to each of these, supplying accurate spectral indices, except in HB 21 case where spectrum is curved. The obtained radio spectra of the loops are fitted rather well by power-low spectra which is consistent with an SNR origin for these features.
- We derived the $T - T$ plots which enables calculation of spectral indices, also.
- From the spectral index analysis we can confirm that the emission from the radio loops is non-thermal in origin, and from the HB 21 emission has synchrotron and thermal component.

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References

Berkhuijsen, E.M. : 1972, *Astron. Astrophys. Suppl.*, **5**, 263.
Borka, V., Milogradov-Turin, J., Urošević, D.: 2006, *Publ. Astron. Obs. Belgrade*, **80**, 61.
Borka, V.: 2006, *Book of contributed papers of the 23rd SPIG*, p. 599.
Borka, V.: 2007, *Mon. Not. R. Astron. Soc.*, **376**, 634.
Borka, V., Milogradov-Turin, J., Urošević, D.: 2008, *Astron. Nachr.* **329**, 397.
Borka Jovanović, V., Urošević, D.: 2008, *Publ. Astron. Obs. Belgrade*, **84**, 459.
Borka Jovanović, V., Urošević, D.: 2009a, *Astron. Nachr.*, **330**, 741.
Borka Jovanović, V., Urošević, D.: 2009b, *Publ. Astron. Obs. Belgrade*, **86**, 101.
Borka Jovanović, V., Urošević, D.: 2010, *Journ. Phys: Conf. Ser.*, **257**, 012030.
Borka Jovanović, V., Urošević, D.: 2011, *Rev. Mex. AA*, **47**, 159.
Borka, D., Borka Jovanović, V., Urošević, D.: 2012, *Rev. Mex. AA*, **48**, 53.
Dwarakanath, K. S., Udaya Shankar, N.: 1990, *J. Astrophys. Astron.*, **11**, 323.

Green, D. A.: 2009a, A Catalogue of Galactic Supernova Remnants (2009 March version), Astrophysics Group, Cavendish Laboratory, Cambridge, United Kingdom (available at http://www.mrao.cam.ac.uk/surveys/snrs/).
Green, D. A.: 2009b, *Bull. Astron. Soc. India*, **37**, 45.
Haslam, C. G. T., Salter, C. J., Stoffel, H., Wilson, W. E.: 1982, *Astron. Astrophys. Suppl.*, **47**, 1.
Leahy, D. A.: 2006, *Astrophys. J.*, **647**, 1125.
Reich, P., Reich, W.: 1986, *Astron. Astrophys. Suppl.*, **63**, 205.
Reif, K., Reich, W., Steffen, P., Müller, P., Weiland, H.: 1987, *Mitt. Astron. Ges.*, **70**, 419.
Roger, R. S., Costain, C. H., Landecker, T. L., Swerdlyk, C. M.: 1999, *Astron. Astrophys. Suppl.*, **137**, 7.
Urošević, D., Borka Jovanović, V.: 2011, *OAJ*, **4**, 218.
Uyaniker, B., Reich, W., Yar, A., Furst, E.: 2004, *Astron. Astrophys.* **426**, 909.