Publ. Astron. Obs. Belgrade No. 86 (2009), 101 - 106 *Contributed paper*

THE CYGNUS RADIO LOOP: TEMPERATURE AND BRIGHTNESS

V. BORKA JOVANOVIĆ[1] and D. UROŠEVIĆ[2]

[1]*Laboratory of Physics (010), Vinča Institute of Nuclear Sciences, P. O. Box 522, 11001 Belgrade, Serbia*
E–mail: vborka@vinca.rs

[2]*Department of Astronomy, Faculty of Mathematics, University of Belgrade, Studentski trg 16, 11000 Belgrade, Serbia*

Abstract. Observations of the continuum radio emission at 1420, 820 and 408 MHz enabled estimations of the brightness of the Cygnus Loop supernova remnant (SNR). We calculated the mean brightness temperatures and surface brightnesses of this loop at the three frequencies.

1. INTRODUCTION

The radio loops probably represent evolved supernova remnants (SNRs) which material expands inside bubbles of low density. Bubbles are made by former SNR explosions or by strong stellar winds (Salter 1983, McKee and Ostriker 1977 and references therein). The radio emission from SNRs is generally understood to be synchrotron emission from the relativistic electrons moving in the magnetic field.

The Cygnus Loop is a large ($\sim 3^\circ$) nearby (~ 1 kpc) SNR of type S. It is listed in Green's catalogue of SNRs as G74.0-8.5 (Green 2004, 2006).

A star in the constellation of Cygnus exploded and its remnant is Cygnus Loop. As shown in Green (1984), it is a relatively old (tens of thousands of years) remnant that has been decelerated considerably by its interaction with the surrounding interstellar medium. Uyaniker et al. (2002) suggested that two overlapping remnants make Cygnus Loop. Additionally, several compact radio sources are located within the boundary of the remnant. In the radio, optical and X-ray band, the characteristics are: (a) in radio band: it is shell, brightest to the north-east, with fainter breakout region to south, with spectral variations, (b) optical: large filamentary loop, brightest to the north-east, not well defined to the south and west, (c) X-ray: shell in soft X-rays (see e.g. in Green 2006). Some radio maps including this remnant are the following: the map by Keen et al. (1973) at 2695 MHz, Dickel and Willis (1980) at 610 MHz, Green (1984) at 408 MHz. We found radio surveys in the electronic form at 1420, 820 and 408 MHz by Reich and Reich (1986), Berkhuijsen (1972) and Haslam et al. (1982), respectively, and used them in this paper.

The Cygnus Loop is classified as a middle-aged SNR located below (but near the plane of) the Galactic equator less than 1 kpc away from us. Its large size and low probability of being confused with Galactic emission makes it ideal for testing evolutionary and structural theories of SNRs.

The goal of this paper is to calculate the average brightness temperatures and surface brightnesses of the Cygnus radio loop at 1420, 820 and 408 MHz and to study how these results are getting along with previous results (Roger et al. 1999, Reich et al. 2003) and with current theories of SNR evolution. These theories predict that loops are non-thermal sources which are spreading inside the hot and low density bubbles made by former supernova explosions or by strong stellar winds (see Salter 1983, McKee and Ostriker 1977 and references therein).

2. ANALYSIS

2. 1. DATA

In this paper we used observations from several radio-continuum surveys given in FITS (Flexible Image Transport System) format. The radio continuum surveys at 1420 MHz (Reich and Reich 1986), 820 MHz (Berkhuijsen 1972) and 408 MHz (Haslam et al. 1982) are used as the basic source of data in this paper. Only these surveys are available in electronic form on MPIfR's Survey Sampler ("Max-Planck-Institut für Radioastronomie", Bonn). This is an online service (http://www.mpifr-bonn.mpg.de/survey.html), which allows users to pick a region of the sky and obtain images and data at different frequencies. The 1420-MHz Stockert survey (Reich and Reich 1986) has the angular resolution of 35′, the 820-MHz Dwingeloo survey (Berkhuijsen 1972) 1°.2 and the 408-MHz all-sky survey (Haslam et al. 1982) 0°.85. The corresponding observations are given at the following rates (measured data) for both l and b: $0\overset{\circ}{.}25$ at 1420 MHz, $0\overset{\circ}{.}5$ at 820 MHz and $0\overset{\circ}{.}33$ at 408 MHz. The effective sensitivities are about 50 mK T_b (T_b is for an average brightness temperature), 0.20 K and about 1.0 K, respectively.

FITS format is primarily designed to store scientific data sets consisting of multidimensional arrays and 2-dimensional tables containing rows and columns of data. We extracted observed brightness temperatures from FITS format into ASCII data files, and afterwards these data files have been processed by our software, i.e. we have developed several programs in C and FORTRAN in order to obtain results presented in this paper.

2. 2. METHOD

The area of Cygnus Loop is very difficult to determine precisely due to great influence of background radiation and superposed external sources. In order to make better estimates of the loop boundaries, we analyzed temperature profiles as explained latter. An example is given in Fig. 1.

The area of Cygnus Loop is inside brightness temperature contours (see Fig. 2). These contour lines correspond to the brightness temperatures: minimum, maximum and nine contours in between. The space between minimum and maximum contours defines our loop. A more complete description of method of calculation is given in Borka (2007) and Borka et al. (2008). The Galactic longitude and latitude intervals for spurs belonging to Cygnus Loop are the following: l = [76.5°, 71.5°], b = [-10.5°, -7°].

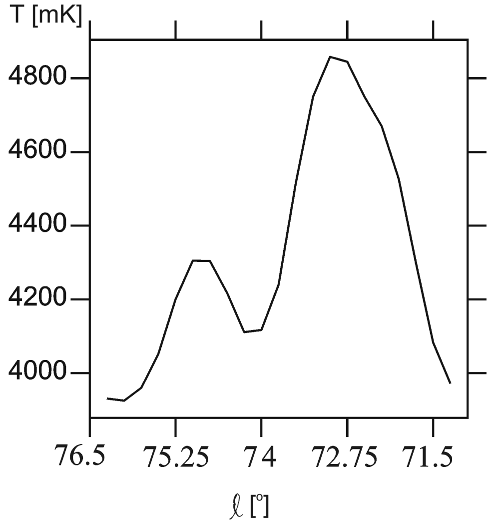

Figure 1: Temperature profile at 1420 MHz for Galactic longitude from 76.5° to 71.5° and for -9° of Galactic latitude. Temperatures are given in mK, and Galactic longitudes in degrees.

The mean temperatures and surface brightnesses of this radio loop are computed using data taken from radio-continuum surveys at 1420, 820 and 408 MHz. We have subtracted the background radiation, as well as the superposed radiation, in order to derive the mean brightness temperature of the SNR alone.

After deriving the mean brightness temperatures T_ν, we derived surface brightnesses Σ_ν by:

$$\Sigma_\nu = \left(2k\nu^2/c^2\right) T_\nu. \tag{1}$$

3. RESULTS

For deriving temperatures over the Cygnus Loop, the areas used for the loop were obtained from the radio continuum maps. The areas over which an average brightness temperature is determined at each of the three frequencies are taken to be as similar as possible within the limits of measurement accuracy. However, some differences between these areas still remain and we think that the major causes of differing borders between the three frequencies are small random and systematic errors in the data. The surface brightnesses of SNRs must be above the sensitivity limit of the observations and must be clearly distinguishable from the Galactic background emission (Green 1991). Therefore, the data from the fainter parts of the loop (which are very low-surface-brightness SNRs) are not taken into account because it is very difficult to resolve them from the background. On the other hand, this would significantly reduce

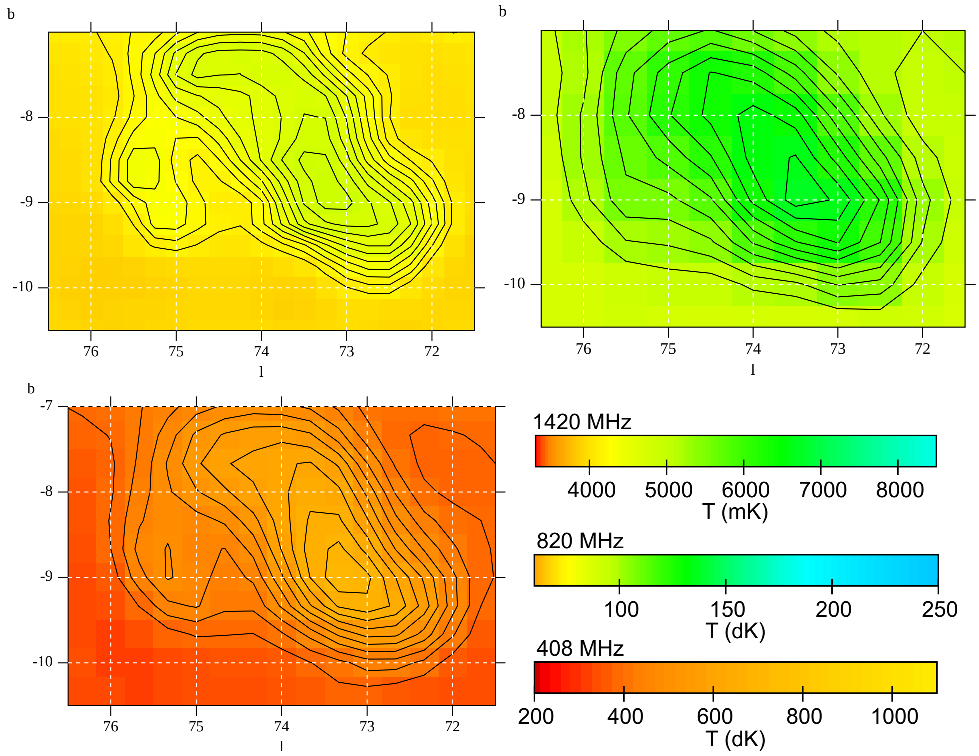

Figure 2: The area of Cygnus Loop at 1420, 820 and 408 MHz, in new galactic coordinates (l, b), showing contours of brightness temperature. Eleven contours plotted represent the temperatures $T_{\rm min}$ and $T_{\rm max}$ from Table 1 and nine contours in between. This radio loop has position: l = [76.5°, 71.5°]; b = [-10.5°, -7°]. **Top left:** the 1420 MHz map with contours of $T_{\rm b}$ given in units of mK. The contours are plotted every 80 mK starting from the lowest temperature of 4100 mK up to 4900 mK. **Top right:** the 820 MHz map with $T_{\rm b}$ in dK. The contours are plotted every 4.4 dK starting from 96 dK up to 140 dK. **Bottom left:** the 408 MHz map with $T_{\rm b}$ in dK. The contours are plotted every 33 dK starting from 390 dK up to 720 dK. **Bottom right:** temperature colorbars for 1420, 820 and 408 MHz, in mK, dK and dK, respectively.

average brightness of entire loop. For evaluation brightness temperatures over the spurs we had to take into account background radiation (Webster 1974). Borders enclosing the spurs are defined to separate the spur and its background. For the method of calculation see Borka (2007).

The results are given in Table 1. $T_{\rm min}$, given in the second column of the table, is the lower temperature limit, while $T_{\rm max}$ is the upper temperature limit. There are some other sources (superposed over the side of the loop) above it and they do not affect the calculation. These temperature limits enable us to distinguish the loop from background and also from external sources. Then we derived the surface brightnesses using equation (1) for each frequency.

Table 1: Temperatures and brightnesses of Cygnus radio loop at 1420, 820 and 408 MHz.

frequency (MHz)	temperature limits $T_{\min}, T_{\max}$ (K)	temperature (K)	brightness (10^{-22} W/(m^2 Hz Sr))
1420	4.1, 4.9	0.45 ± 0.05	2.80 ± 0.30
820	9.6, 14	2.10 ± 0.20	4.33 ± 0.40
408	39, 72	14.4 ± 1.0	7.37 ± 0.50

When we transform our brightnesses into the flux density in Jy, and then calculate values at 1000 MHz for comparison, it can be noticed that our flux densities agree with previous data transformed at 1000 MHz: Roger et al. (1999) derived flux density for Cygnus Loop at 22 MHz (S_ν = 1378 Jy) and Reich et al. (2003) at 863 MHz (S_ν = 184 Jy). The other way for comparison is to transform their calculated fluxes into brightnesses at 1000 MHz. Using loop size $\Omega = 240' \times 170'$ from Reich et al. (2003) and spectral index $\beta = 2.49$ from Trushkin (2002), we reduced the flux densities given in Jy to brightnesses given in $10^{-22}\,\mathrm{W/(m^2\,Hz\,Sr)}$ by:

$$B_\nu = S_\nu \times 10^{-26}/\Omega. \tag{2}$$

Then we reduced B_ν to 1000 MHz using:

$$B_{1000} = B_\nu (1000/\nu)^{(2-\beta)}. \tag{3}$$

From flux densities given in mentioned papers, we calculated the following values for radiation intensities: $B_{1000} = 4.96\times10^{-22}\,\mathrm{W/(m^2\,Hz\,Sr)}$ from flux given in Reich et al. (2003) and $B_{1000} = 6.16\times10^{-22}\,\mathrm{W/(m^2\,Hz\,Sr)}$ from flux given in Roger et al. (1999). Using the same β and applying relation (3) to our calculated values of B_ν at 1420, 820 and 408 MHz, for B_{1000} we obtain: 3.32, 3.93 and 4.75 $\times10^{-22}\,\mathrm{W/(m^2\,Hz\,Sr)}$, respectively.

4. CONCLUSIONS

Observations of the continuum radio emission at 1420, 820 and 408 MHz enabled estimations of the brightness of the Cygnus Loop SNR. The sensitivity of the brightness temperatures are: 50 mK for 1420 MHz, 0.2 K for 820 MHz, and about 1.0 K T_b for 408 MHz. The most precise measurements (the least relative errors) are in case of 1420 MHz, therefore positions of the brightness temperature contours of the loop are the most realistic for this frequency.

In this paper we calculated the brightness temperatures and surface brightnesses of the Cygnus radio loop at 1420, 820 and 408 MHz. We determined average brightness temperature from a region, after subtraction of a background level. Our values (reduced to 1000 MHz for comparison) are in good agreement with the earlier results.

The optical proper motion and the shock velocity gives 0.44 kpc for distance to Cygnus Loop (Green 2006), while some other observations suggest 0.5 - 0.8 kpc (Leahy and Roger 1998). With new derived brightnesses, it is possible to calculate new diameters and distances to this loop at the three frequencies: 1420, 820 and 408 MHz and then to estimate some average distance.

References

Borka, V.: 2007, *Mon. Not. R. Astron. Soc.*, **376**, 634.
Borka, V., Milogradov-Turin, J., Urošević, D.: 2008, *Astron. Nachr.*, **329**, 397.
Berkhuijsen, E. M.: 1972, *A&AS*, **5**, 263.
Davies, R. D.: 1963, *Observatory*, **83**, 172.
Dickel, J. R., Willis, A. G.: 1980, *Astron. Astrophys.*, **85**, 55.
Green, D. A.: 1984, *Mon. Not. R. Astron. Soc.*, **211**, 433.
Green, D. A.: 1991, *Publ. Astron. Soc. Pacific*, **103**, 209.
Green, D. A.: 2004, *Bull. Astron. Soc. India*, **32**, 335.
Green, D. A.: 2006, A Catalogue of Galactic Supernova Remnants (2006 April version), Cavendish Laboratory, Cambridge, UK.
Haslam, C. G. T., Salter, C. J., Stoffel, H., Wilson, W. E.: 1982, *A&AS*, **47**, 1.
Keen, N. J., Wilson, W. E., Haslam, C. G. Y., Graham, D. A., Thomasson, P.: 1973, *Astron. Astrophys.*, **28**, 197.
Leahy, D. A., Roger, R. S.: 1998, *Astrophys. J.*, **505**, 784.
McKee, C. F., Ostriker, J. P.: 1977, *Astrophys. J.*, **218**, 148.
Reich, P., Reich, W.: 1986, *A&AS*, **63**, 205.
Reich, W., Zhang, X., Fürst, E.: 2003, *Astron. Astrophys.*, **408**, 961.
Roger, R. S., Costain, C. H., Landecker, T. L., Swerdlyk, C. M.: 1999, *A&AS*, **137**, 7.
Salter, C. J.: 1983, *Bull. Astron. Soc. India*, **11**, 1.
Trushkin, S. A.: 2002, http://cats.sao.ru
Uyaniker, B., Reich, W., Yar, A., Kothes, R., Fürst, E.: 2002, *Astron. Astrophys.*, **389**, L61.
Webster, A. S.: 1974, *Mon. Not. R. Astron. Soc.*, **166**, 355.