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THE ANALYSIS OF THE POSSIBLE THERMAL EMISSION AT RADIO FREQUENCIES FROM AN EVOLVED SUPERNOVA REMNANT HB 3 (G132.7+1.3): REVISITED

D. Onić and D. Urošević

Department of Astronomy, Faculty of Mathematics, University of Belgrade, Studentski trg 16, 11000 Belgrade, Serbia

E–mail: *donic@matf.bg.ac.yu*

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SUMMARY: It has recently been reported that some of the flux density values for an evolved supernova remnant (SNR) HB 3 (G132.7+1.3) are not accurate enough. In this work we therefore revised the analysis of the possible thermal emission at radio frequencies from this SNR using the recently published, corrected flux density values. A model including the sum of non-thermal (purely synchrotron) and thermal (bremsstrahlung) components is applied to fit the integrated radio spectrum of this SNR. The contribution of thermal component to the total volume emissivity at 1 GHz is estimated to be $\approx 37\%$. The ambient density is also estimated to be $n \approx 9$ cm^{-3} for T $= 10^4$ K. Again we obtained a relatively significant presence of thermal emission at radio frequencies from the SNR, which can support interaction between SNR HB 3 and adjacent molecular cloud associated with the H II region W3. Our model estimates for thermal component contribution to total volume emissivity at 1 GHz and ambient density are similar to those obtained earlier (≈ 40 %, ≈ 10 cm^{-3}). It is thus obvious that the corrected flux density values do not affect the basic conclusions.

Key words. Radiation mechanisms: thermal – Radio continuum: general –ISM: supernova remnants – ISM: individual objects: HB3

1. INTRODUCTION

The presence of thermal emission at radio frequencies may be a useful tool in identifying interactions between supernova remnants (SNRs) and molecular clouds, and also in estimating the ambient density near SNRs using radio continuum data (Urošević and Pannuti 2005, Urošević et al. 2007). In this work we argue for the presence of a thermal bremsstrahlung component in the radio emission from SNR HB 3 in addition to the synchrotron component. SNRs can be sources with significant amount of thermal radiation, and as Urošević and Pannuti (2005) stated, there are two basic criteria for the production of a significant amount of radio emission through the thermal bremsstrahlung process from an SNR: the SNR evolves in an environment denser than the average, and its temperature must be lower than the average (but always higher then the recombination temperature). Two cases have been considered: thermal emission at radio frequencies from a relatively young SNR evolving in a dense molecular cloud environment ($n \approx 100 - 1000$ cm^{-3}), and an extremely evolved SNR (approximately $10^5 - 10^6$ years old) expanding in a dense warm medium ($n \approx 1 - 10$ cm^{-3}).

Urošević et al. (2007) analysed the broadband ($22-3900$ MHz) radio spectrum of the Galactic SNR HB 3 and discussed the possible thermal radio emission from the SNR. Observations published earlier have revealed that a curvature is present in the radio spectrum of SNR HB 3, indicating that a single synchrotron component appears insufficient to adequately fit the radio spectrum. They have suggested that a more natural explanation for the apparent spectral index variations found by Tian and Leahy (2005) is synchrotron emission, which dominates at lower frequencies, and bremsstrahlung emission, which dominates at higher frequencies. Urošević et al. (2007) have found ≈ 40 % for the thermal component contribution to total volume emissivity at 1 GHz and have also estimated the ambient density, implied by the presence of thermal component, to be ≈ 10 cm^{-3}. Green (2007) has recently reviewed the radio spectrum of SNR HB 3, noting the difficulties in deriving accurate flux densities for the remnant, particularly at higher frequencies, due to thermal emission from the nearby bright H II region W3 (IC 1795) and its surroundings. He pointed out that some of the previously published flux density values used by Urošević et al. (2007) are not accurate enough and that the spectrum of the SNR is satisfactorily represented by a simple power low spectrum, as well as that the contamination with thermal emission from adjacent regions is the cause of the reported spectral flattening of the spectrum. In this work we present the results of our analysis using recently reported by Green, corrected flux densities for SNR HB 3.

2. THE MODEL

A spectrum of an SNR in radio domain is usually represented by an ordinary power law. If the frequency is in GHz, the flux density can be represented by the following expression:

$$S_\nu = S_{1\,\mathrm{GHz}} \cdot \nu^{-\alpha}, \qquad (1)$$

where $S_{1\,\mathrm{GHz}}$ is the flux density at 1 GHz, and α is the radio spectral index. In order to distinguish the contribution of thermal and non-thermal component to the total radiation, SNR radio integrated spectrum was fitted to a simple sum of these two components. If the frequencies are still in GHz, the relation for the flux density can be written as follows:

$$S_\nu = S^{\mathrm{NT}}_{1\,\mathrm{GHz}}\ (\nu^{-\alpha} + \frac{S^{\mathrm{T}}_{1\,\mathrm{GHz}}}{S^{\mathrm{NT}}_{1\,\mathrm{GHz}}}\ \nu^{-0.1}), \qquad (2)$$

where $S^{\mathrm{T}}_{1\,\mathrm{GHz}}$ and $S^{\mathrm{NT}}_{1\,\mathrm{GHz}}$ are flux densities corresponding to thermal and non-thermal component, respectively at 1 GHz. The spectral index is considered to be constant in the SNR shell. It is also taken that the thermal radiation is optically thin and has the spectral index equal to 0.1 at any point. As the radio frequency increases, the amount of synchrotron radiation from an SNR decreases and the contribution of thermal bremsstrahlung emission becomes more significant. In our model it is also considered that the synchrotron radiation, optically thin at any point, is not absorbed or scattered by thermal gas.

The volume emissivity of thermal bremsstrahlung radiation for an ionized gas cloud is proportional to the square of the electron (or ion) volume density n:

$$\varepsilon_\nu = 7 \times 10^{-38} n^2 T^{-\frac{1}{2}}, \qquad (3)$$

where n is in cm^{-3} and thermodynamical temperature T in K. Having determined total ε_ν and thermal component contribution to total volume emissivity, the density of the interstellar medium (ISM) can be estimated using Eq. (3).

This model is valid only in the approximation of constant density and temperature. The model itself also presumes a simple sum of non-thermal and thermal component, while the fact that the dependence of flux density could be some other, more complicated, function of thermal and non-thermal components is not considered. It is also important to note that this model, in general, does not distinguish between thermal and non-thermal emission with the same spectral index (i.e. the case of lower synchrotron spectral index).

Despite these drawbacks, our model represents a useful tool for estimating the contribution of thermal bremsstrahlung component to the total volume emissivity and ambient density using radio continuum data.

3. SNR HB 3 (G132.7+1.3)

From the Green (2006) paper, the value of the radio spectral index is 0.4, while $S_{1\,\mathrm{GHz}} = 45$ Jy, the size is around 80 arcmin and the SNR is S (shell) type. On the other hand, a combination of radio shell morphology with a center-filled thermal X-ray morphology has led to the classification of SNR HB 3 as a mixed-morphology SNR. It is the one of the largest SNRs currently known. The distance to the SNR is about 2.2 kpc (Tian and Leahy 2005, Shi et al. 2008). SNR HB 3 size, based on a distance of 2 kpc is 60×80 pc. Lazendić and Slane (2006) stated that the SNR is 90×120 arcmin in diameter. Kovalenko, Pynzar and Udal'tsov (1994) reported: $\alpha = (0.51 \pm 0.12)$, Fesen et al. (1995): $\alpha = (0.64 \pm 0.01)$ (also pointed out by Lazendić and Slane 2006) and Landecker et al. (1987): $\alpha = (0.60 \pm 0.04)$. Green (2007) has found $\alpha = (0.56 \pm 0.03)$. Tian and Leahy (2005) indicated spectral index variations with majority of values between 0.3 and 0.7.

Shi et al. (2008) extracted 4800 MHz total intensity and polarization data of HB 3 from the Sino-German 6 cm polarization survey of the Galactic plane made with the Urumqi 25 m telescope, but they could not give a total flux density at 4800 MHz of the whole SNR because of a low resolution. They have found a radio spectral index of HB 3 of $\alpha = -(0.61 \pm 0.06)$ using only three flux densities, at

1408 MHz, 2695 MHz and 4800 MHz, and concluded that there is no spectral flattening at high frequencies. Shi et al. (2008) also pointed out that a reliable observations of SNR HB 3 at frequencies above 3000 MHz are crucial to confirm a spectral flattening.

A radio pulsar PSR J0215+6218 has been discovered within (in projection) the SNR HB 3 boundaries, but it appears to be much older than the remnant and therefore not associated with the SNR (Lazendić and Slane 2006, Lorimer et al. 1998).

Fesen et al. (1995) stated that SNR HB 3 is relatively optically faint SNR. Diffuse and filamentary optical emission has been detected from the SNR, with the strongest emission along the western SNR shell (Lazendić and Slane 2006). Reich et al. (2003) indicated that the SNR radio shell is located at the western edge of the H II region complex W3-W4-W5. Optical emission from the SNR was found to be well-correlated with the radio emission, with a multiple shock structure found in the western SNR shell and lack of emission in the southeast region.

Most of the mixed-morphology SNRs are interacting with molecular or H I clouds, as indicated in some cases by infrared line emission or OH masers (Rho and Petre 1998). OH (1720 MHz) masers, which are recognized as a diagnostic mean for a molecular cloud interaction with a SNR, have been detected towards the W3/HB 3 complex (Lazendić and Slane 2006, Koralesky et al. 1998).

Urošević et al. (2007) showed that the X-ray emission is seen to lie entirely within the radio shell of HB 3. To obtain an independent estimate of the ambient density of the ISM surrounding HB 3, they performed spectral fitting on the extracted *ASCA* GIS spectra and calculated electron densities to be $n_e \approx 0.4 f^{-1/2}$ cm^{-3} for the central region and $n_e \approx 0.1 f^{-1/2}$ cm^{-3} for the northern and southern regions (see Table 2 in Urošević et al. 2007), where f represents the volume filling factor.

4. ANALYSIS AND RESULTS

Green (2007) pointed out that the radio observations of the SNR HB 3 are complicated by the overlapping thermal emission from an adjacent H II region W3. He has shown that some of the previously published flux density values (used by Urošević et al. 2007 in their analysis) are not accurate enough. Green (2007) again tackled the problem of deriving the accurate flux density values and listed the corrected values for SNR HB 3. in particular, he reported corrected values for 408 MHz and 1420 MHz points and also corrected uncertainty for 865 MHz point, all from Tian and Leahy (2005). He also derived an integrated flux density for the Effelsberg 2695 MHz survey data. Green excluded 3650 and 3900 MHz points (from Tian and Leahy 2005) due to their possible contamination with thermal emission associated with W3. He also rescaled 22, 38 and 178 MHz points, used by Urošević et al. (2007) to be on the scale of Baars et al. (1977). We have revised the analysis of the possible thermal emission contribution in the total volume emissivity at radio frequencies from an evolved SNR HB 3 using data points for integrated radio flux density from Green (2007) for a range from 22 MHz to 2.695 GHz (see Table 1 in Green 2007).

The parameters of our model fit (Eq. 2) are shown in Table 1. The parameters of purely non-thermal model fit (Eq. 1) can be seen in Table 2.

Note that the radio spectral index value is higher than the value from Green (2006) both for the purely non-thermal ($\alpha = 0.56 \pm 0.02$) and our model fit ($\alpha = 0.70 \pm 0.05$) calculations. The results from the purely non-thermal model fit corresponds to the values from Green (2007). Our model radio spectral index estimate is closer to the value given in Lazendić and Slane (2006) and Fesen et al. (1995) than to the one of Green (2006, 2007). In Fig. 1 the full line represents a fit by non-thermal plus thermal model, while the dotted line represents fit by a purely non-thermal model.

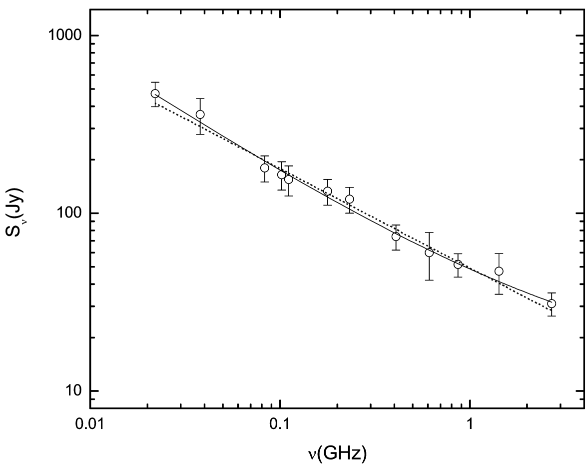

Fig. 1. *The integrated spectrum of HB 3. The full line represents a fit by non-thermal plus thermal model, while the dotted line represents fit by a purely non-thermal model.*

Table 1. The fit parameters for our model for SNR HB3.

α	$S^{\rm NT}_{1\,\rm GHz}$ (Jy)	$\frac{S^{\rm T}_{1\,\rm GHz}}{S^{\rm NT}_{1\,\rm GHz}}$	$\chi^2_{\rm red}$ (dof)	Adj. R^2
0.70 ± 0.05	30.45 ± 5.22	0.59 ± 0.27	0.19 (9)	0.985

Table 2. The fit parameters for purely non-thermal model for SNR HB3.

α	$S^{\mathrm{NT}}_{1\mathrm{GHz}}$ (Jy)	χ^2_{red} (dof)	Adj. R^2
0.56 ± 0.02	49.18 ± 2.06	0.31 (10)	0.976

If a mean value of 37 % for the thermal component contribution to total volume emissivity at 1 GHz is assumed, we get $n \approx 9$ cm^{-3} for the assumed post-shock temperature value of 10^4 K. We have adopted $d = 2$ kpc and $D = 70$ pc for consistency with Urošević et al. (2007). It is clearly seen that, for the corrected integrated flux density values, we also get a relatively significant presence of thermal emission at radio frequencies from the SNR. Our model estimates for thermal component contribution to total volume emissivity at 1 GHz (≈ 37 %) and ambient density (≈ 9 cm^{-3}) are similar to those obtained previously (≈ 40 %, ≈ 10 cm^{-3}) by Urošević et al. (2007). The fact that essentially the same thermal component again minimizes the χ^2, indicates that its presence cannot be ruled out by the corrections to the flux densities.

If we assume the value for the compression parameter to be 4, we can roughly estimate preshock ISM number density as $n_0 \approx 2.25$ cm^{-3} for $T = 10^4$ K.

It is obvious that our ambient density estimates support the possibility that the SNR is indeed expanding in a dense ISM. Based on our analysis we can support the assumption that SNR HB 3 is indeed interacting with the molecular cloud material. The presence of the thermal bremsstrahlung component in the radio spectrum of SNR HB 3 suggests that this SNR is in fact interacting with adjacent molecular cloud associated with the H II region W3.

It should be emphasized that the further measurements at the highest radio frequencies (> 3 GHz) are required for a more detailed analysis of existence of the thermal component in HB3.

5. CONCLUSIONS

In this work we revised an analysis of the possible thermal emission at radio frequencies from an evolved SNR HB 3. Some of the previously published flux density values for SNR HB 3 are shown to be inaccurate. Here we present the results of our analysis using the recently published, corrected, flux densities. The main conclusions are:

1. The contribution of thermal component to the total volume emissivity is estimated to be ≈ 37%, and the ambient density is also estimated to be $n \approx 9$ cm^{-3} for T = 10^4 K.
2. Our model estimates for thermal component contribution to total volume emissivity at 1 GHz and ambient density are similar to those obtained earlier (≈ 40 %, ≈ 10 cm^{-3}). It is clear that the corrected flux density values do not affect the basic conclusions.
3. The presence of the thermal bremsstrahlung component in the radio spectrum of SNR HB 3 suggests that this SNR is in fact interacting with adjacent molecular cloud associated with the H II region W3. The presence of the thermal emission at radio frequencies may be a useful tool for identifying interactions between SNRs and molecular clouds and also for estimating the ambient density near SNRs using the radio continuum data.
4. The lack of data at higher radio frequencies prevents us from giving a definite conclusion about the issue.

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ПОНОВНА АНАЛИЗА МОГУЋЕ ТЕРМАЛНЕ ЕМИСИЈЕ НА РАДИО-ФРЕКВЕНЦИЈАМА ЕВОЛУИРАНОГ ОСТАТКА СУПЕРНОВЕ HB 3

D. Onić and D. Urošević

Department of Astronomy, Faculty of Mathematics, University of Belgrade, Studentski trg 16, 11000 Belgrade, Serbia

E–mail: *donic@matf.bg.ac.yu*

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Оригинални научни рад

Недавно је установљено да су неке од вредности густина флукса еволуираног остатка супернове (ОСН) HB 3 (G132.7+1.3) нетачне. У овом раду смо поновили анализу могуће термалне радио-емисије ОСН HB 3 користећи кориговане вредности густина флукса. Модел који претпоставља суму нетермалне и термалне компоненте примењен је за фитовање радио-спектра остатка. Учешће термалне компоненте у укупној запреминској емисивности на 1 GHz је процењено на ≈ 37 %. Густина околне средине је такође процењена на $n \approx 9$ cm^{-3} за T = 10^4 K. Поново је, дакле, нађено значајно присуство термалне компоненте у укупној запреминској емисивности, тако да можемо да подржимо хипотезу о интеракцији између остатка и молекуларног облака. Процене присуства термалне компоненте у укупној запреминској емисивности на 1 GHz и густине околне средине су сличне са раније одређеним (≈ 40 %, ≈ 10 cm^{-3}). Јасно је да вредности кориговaних густина флукса не мењају основне закључке овог рада.