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

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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. In this work we revised an analysis of the possible thermal emission at radio frequencies from the SNR HB 3 using the recently published, corrected, flux density values. A model including a sum of non-thermal (purely synchrotron) and thermal (bremsstrahlung) component is applied for fitting integrated radio spectrum of the SNR. The contribution of thermal component in total volume emissivity at 1 GHz was estimated to be ≈ 37%. The ambient density was also estimated to be n ≈ 9 cm$^{-3}$ for the T = 10$^4$ K. Again, we obtained the relatively significant presence of thermal emission at radio frequencies from the SNR so we could 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 clear that the corrected flux density values do not change 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 for identifying interactions between supernova remnants (SNRs) and molecular clouds, and also for estimating the ambient density near SNRs using radio continuum data (Urošević & Pannuti 2005, Urošević, Pannuti & Leahy 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. It is possible that SNRs can be sources with significant amount of thermal radiation and as Urošević & 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 greater than 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 ≈ 100 – 1000 cm$^{-3}$) and extremely evolved SNR (approximately 10$^5$ – 10$^6$ years old) expanding...
in a dense warm medium \((n \approx 1 - 10 \, \text{cm}^{-3})\). For a detailed discussion about the issue see Urošević & Pannuti (2005) and Urošević, Pannuti & Leahy (2007).

Urošević, Pannuti & Leahy (2007) have analyzed the broadband \((22 - 3900 \, \text{MHz})\) radio spectrum of the Galactic SNR HB 3 and have discussed the possible thermal radio emission from the SNR. Earlier published observations 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. Urošević, Pannuti & Leahy (2007) have suggested that more natural explanation for the apparent spectral index variations found by Tian & Leahy (2005) is synchrotron emission, which dominates at lower frequencies, and bremsstrahlung emission, which dominates at higher frequencies. They have found \(\approx 40\%\) 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 \(\approx 10 \, \text{cm}^{-3}\). Recently, Green (2007) has 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 HII region W3 (IC 1795) and its surroundings. He pointed out that some of the earlier published flux density values used by Urošević, Pannuti & Leahy (2007) in their analysis are not accurate and that the spectrum of the SNR is well represented by a simple power low spectrum as well as the contamination with thermal emission from adjacent regions is the cause for the reported spectral flattening of the spectrum. In this work we present the results of our analysis using the corrected, recently reported by Green (2007), flux densities for SNR HB 3.

2. The model

A spectrum of SNRs 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:

\[
S_{\nu} = S_{1 \, \text{GHz}} \cdot \nu^{-\alpha},
\]

where: \(S_{1 \, \text{GHz}}\) is the flux density at 1 GHz, and \(\alpha\) is the radio spectral index. In order to distinguish the contribution of thermal and non-thermal component within the total radiation, SNR radio integrated spectrum was fitted by 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:

\[
S_{\nu} = S_{1 \, \text{GHz}}^{\text{NT}} \cdot (\nu^{-\alpha} + \frac{S_{1 \, \text{GHz}}^{T}}{S_{1 \, \text{GHz}}^{\text{NT}}}) \cdot \nu^{-0.1},
\]

where: \(S_{1 \, \text{GHz}}^{\text{NT}}\) and \(S_{1 \, \text{GHz}}^{T}\) are flux densities corresponding to thermal and non-thermal component, respectively. The spectral index is considered to be constant in the SNR shell. It is also considered that the thermal radiation is optically thin and has the spectral index equal 0.1 at any point. As the radio frequency increases, the amount of synchrotron radiation from an SNR decreases and the amount 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 \(n\), i.e.:

\[
\varepsilon_{\nu} = 7 \times 10^{-38} \, n^2 \, T^{-\frac{1}{2}},
\]

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

This model is valid only in the approximation of constant density and temperature. The model itself also assumes a simple sum of non-thermal and thermal component, while the attention is not paid to the fact that the dependence of flux density could be another, more complicated, function of thermal and non-thermal components. 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, $S_1^{1.1GHz} = 45 \text{ Jy}$, 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 (Urošević, Pannuti & Leahy 2007 and references therein). It is the one of the largest SNRs currently known (Fesen et al. 1995, Tian & Leahy 2005). The distance from the SNR is about 2.2 kpc (Tian & Leahy 2005, Shi et al. 2008). SNR HB 3 size, based on a distance of 2 kpc is $60 \times 80$ pc (Tian & Leahy 2005 and references therein). Lazendić & Slane (2006) stated that the SNR is 90 $\times$ 120 arcmin in diameter. Kovalenko, Pynzar & Udal’tsov (1994) have reported: $\alpha = (0.51 \pm 0.12)$, Fesen et al. (1995): $\alpha = (0.64 \pm 0.01)$ (also pointed by Lazendić & Slane 2006) and Landecker et al. (1987): $\alpha = (0.60 \pm 0.04)$. Green (2007) has found $\alpha = (0.56 \pm 0.03)$. Tian & Leahy (2005) pointed spectral index variations with most values between 0.3 and 0.7.

Shi et al. (2008) have 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 have concluded that there is no spectral flattening at high frequencies. Shi et al. (2008) have also pointed out that 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 boundary, but it appears to be much older than the remnant and therefore not associated with the SNR (Lazendić & Slane 2006, Lorimer, Lyne & Camilo 1998).

Fesen et al. (1995) pointed 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 and lack of emission in the southeast region (Lazendić & Slane 2006 and references therein).

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 & Petre 1998). OH (1720 MHz) masers, which are recognized as a diagnostic for a molecular cloud interaction with a SNR, have been detected towards the W3/HB 3 complex (Lazendić & Slane 2006, Koralesky et al. 1998).

Urošević, Pannuti & Leahy (2007) pointed 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 have performed spectral fitting on the extracted ASCA GIS spectra and have 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, Pannuti & Leahy 2007), where $f$ represents the volume filling factor.

Analysis and results

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

The parameters of our model fit (equation 2) are as follows: $\alpha = (0.70 \pm 0.05)$, $S_1^{1.1GHz} = (30.45 \pm 5.22)$ Jy, $S_1^{1.1GHz}/S_1^{1GHz} = (0.59 \pm 0.27)$, $\chi^2_{\text{red}} = 0.19$, 9 degrees of freedom (dof) as it can be seen in Table 1. $\chi^2_{\text{red}}$ represents reduced $\chi^2$ ($\chi^2$/dof). The parameters of purely non-thermal model fit (equation 1) are as follows: $\alpha = (0.56 \pm 0.02)$, $S_1^{1GHz} = (49.18 \pm 2.06)$ Jy, $\chi^2_{\text{red}} = 0.31$, 10 dof as it can be seen in Table 2.
Table 1. The fit parameters for our model for SNR HB3.

| $\alpha$  | $S_{1\text{GHz}}^{NT} (\text{Jy})$ | $\frac{S_{1\text{GHz}}^{thermal}}{S_{1\text{GHz}}^{NT}}$ | $\chi^2_{\text{red}}$ (dof) |
|-----------|----------------------------------|---------------------------------|---------------------|
| 0.70 ± 0.05 | 30.45 ± 5.22                     | 0.59 ± 0.27                    | 0.19 (9)            |

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

| $\alpha$  | $S_{1\text{GHz}}^{NT} (\text{Jy})$ | $\chi^2_{\text{red}}$ (dof) |
|-----------|----------------------------------|---------------------|
| 0.56 ± 0.02 | 49.18 ± 2.06                    | 0.31 (10)           |

It can be noted that the radio spectral index value is higher than the value from Green (2006) both for the purely non-thermal ($\alpha = 0.56 ± 0.02$) and our model fit ($\alpha = 0.70 ± 0.05$) calculations. The results from the purely non-thermal model fit responds to the values placed in Green (2007). Our model fit radio spectral index estimate is closer to the value placed in Lazendić & Slane (2006) and Fesen et al. (1995) than in Green (2006, 2007). Figure 1 shows in a solid line fit by non-thermal plus thermal model, while the dotted line shows the fit by purely non-thermal model through the given sample.

![Figure 1](image1.png)

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

If a mean value of 37%, from our analysis, for the thermal component contribution to total volume emissivity at 1 GHz is assumed, we get $n \approx 9 \text{ cm}^{-3}$ for the assumed post-shock temperature value of $10^4 \text{ K}$. We have assumed $d = 2$ kpc and $D = 70$ pc for consistency with Urošević, Panmuti & Leahy (2007). It is clearly seen that for the corrected integrated flux density values we also get the 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 ($\approx 37\%$) and ambient density ($\approx 9 \text{ cm}^{-3}$) are similar to those obtained earlier ($\approx 40\%$, $\approx 10 \text{ cm}^{-3}$) by Urošević, Panmuti & Leahy (2007). The fact that essentially the same thermal component again minimizes the $\chi^2$ 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 pre-shock ISM number density as $n_0 \approx 2.25 \text{ cm}^{-3}$ for $T = 10^4 \text{ K}$.

It is clearly visible that our ambient density estimates could support the possibility that the SNR is indeed expanding in a dense ISM. Based on our analysis we can support the possibility 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 HII region W3.

It should be pointed out that the further measurements at the highest radio frequencies ($> 3$ GHz) are required for a detailed discussion of the issue.

### 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 earlier published flux density values for SNR HB 3 are shown to be non-accurate. Here we present the results of our analysis using the recently published, corrected, flux densities so the main conclusions are:

1. The contribution of thermal component in total volume emissivity was estimated to be $\approx 37\%$ and the ambient density was also estimated to be $n \approx 9 \text{ cm}^{-3}$ for the $T = 10^4 \text{ K}$.
2. Our model estimates for thermal component contribution to total volume emissivity at 1 GHz and ambient density are similar to those obtained earlier ($\approx 40\%$, $\approx 10 \text{ cm}^{-3}$). It is clear that the corrected flux density values do not change 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 HII region W3. The presence of 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 unable us to give a firmer conclusion about the issue.

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

| $\alpha$  | $S_{1\text{GHz}}^{NT} (\text{Jy})$ | $\frac{S_{1\text{GHz}}^{thermal}}{S_{1\text{GHz}}^{NT}}$ | $\chi^2_{\text{red}}$ (dof) |
|-----------|----------------------------------|---------------------------------|---------------------|
| 0.70 ± 0.05 | 30.45 ± 5.22                     | 0.59 ± 0.27                    | 0.19 (9)            |

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

| $\alpha$  | $S_{1\text{GHz}}^{NT} (\text{Jy})$ | $\chi^2_{\text{red}}$ (dof) |
|-----------|----------------------------------|---------------------|
| 0.56 ± 0.02 | 49.18 ± 2.06                    | 0.31 (10)           |

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

Baars, J. W. M., Genzel, R., Pauliny-Toth, I. I. K., Witzel, A., 1977, A&A, 61, 99
Fesen, R. A., Downes, R. A., Wallace, D., Normandeanu, M., 1995, AJ, 110, 2876
Green, D. A., 2007, BASI, 35, 77
Green, D. A., 2006, A catalogue of Galactic Supernova Remnants (2006 April version), Astrophysics Group, Cavendish Laboratory, Cambridge, http://www.mrao.cam.ac.uk/surveys/snrs/
Koralesky, B., Frail, D. A., Goss, W. M., Claussen, M. J., Green, A. J., 1998, AJ, 116, 1323
Kovaleko, A. V., Pynzar, A. V., Udaltsov, V. A., 1994, ARep, 38, 95
Landecker, T. L., Vaneldik, J. F., Dewdney, P. E., Routledge, D., 1987, AJ, 94, 111
Lazendić, J. S., Slane, P. O., 2006, ApJ, 647, 350
Lorimer, D. R., Lyne, A. G., Camilo, F., 1998, A&A, 331, 1002
Reich, W., Zhang, X., Fürst, E., 2003, A&A, 408, 961
Rho, J., Petre, R., 1998, ApJ, 503, L167
Routledge, D., Dewdney, P. E., Landecker, T. L., Vaneldik, J. F., 1991, A&A, 274, 529
Shi, W. B., Han, J. L., Gao, X. Y., Sun, X. H., Xiao, L., Reich, P. and Reich, W., 2008, A&A, arXiv:0806.1647
Tian, W., Leahy, D., 2005, A&A, 436, 187
Urošević D, Pannuti T. G., 2005, Astropart. Phys., 23, 577
Urošević D, Pannuti T. G., Leahy D., 2007, ApJ, 655, L41
АНАЛИЗА МОГУЋЕ ТЕРМАЛНЕ ЕМИСИЈЕ НА РАДИО ФРЕКВЕНЦИЈАМА ЕВОЛУИРАНГ ОСТАТКА ХБЗ

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УДК
Претходно савиштење

Недавно је објављено 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 недавно публиковане, кориговане вредности, густина флукса. Модел који претпоставља суму нетермалне и термалне компоненте је примењен за фитовање радио-спектра остатка. Присуство термалне компоненте у укупној запреминској емисивности на 1 GHz је проценено на ≈ 37 %. Густина околне средине је такође проценена на n ≈ 9 cm−3 за T = 10⁴ K. Поново је одређено значајно присуство термалне компоненте у укупној запреминској емисивности тако да можемо да подупремо хипотезу о интеракцији између остатка и молекулярног облака. Прцене 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 видљиво да вредности коригованих густина флукса не мењају основне закључке.