Studio of Radio Emission from Supernova Remnants

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Abstract: The properties of two supernova remnants, SNR 3C 391 and SN 1006, are theoretically re-analyzed. Comparing data from previous studies ([6] and [9]) with theoretical models we determine astronomical parameters such as the spectral index, optical depth, magnetic field and flux density at key frequencies. A weighted least-squares fit of the data will allow us to study the turnover for low frequencies in the continuum spectrum of SNR 3C 391 caused by free-free thermal absorption of a gas directly linked to the remnant. Multiple origins of the ionized absorbing gas are discussed, such as a warm ionized medium, HII regions and the encounter of the supernova remnants shock wave with a molecular cloud. On the other hand, a linear least-squares fit is the method chosen for studying the continuum spectrum for SN 1006. Comparing our results with the ones obtained by Berezhko et al. 2012 using the kinetic theory of cosmic rays we will be able to prove the consistency of this theory.

I. INTRODUCTION

Supernova explosions eject large amount of mass and energy, transforming the surrounding interstellar medium, triggering the formation of new stars and changing the balance of galaxies. Thus, supernova are an important object of study in order to understand astrophysical processes such as star formation or the origin of Cosmic Rays.

It is commonly believed that Galactic Cosmic Rays are accelerated in shell-type supernova remnants. In order to prove this hypothesis we need a list of supernova remnants and their astronomical parameters precisely determined. Comparing this information with theoretical models should prove the veracity of the hypothesis.

It is interesting to focus this study on type Ia supernova, since they come from rather old and low-mass stars, leading to a remnant with almost a uniform circumstellar medium and will also restrict the amount of energy and mass ejected, avoiding winds in the interior of the remnant. This will simplify the study and avoid more complex results.

This study is focused on synchrotron emission in the radio and X-ray ranges from two different supernova remnants. We will obtain the astronomical parameters required in order to understand their emission spectrum.

In this work we have chosen to study the supernova remnants SNR 3C 391 and SN 1006. SNR 3C 391 is a supernova known to have a turnover for low frequencies due to free-free absorption of ionized thermal gas linked to the supernova. SN 1006 is a Type Ia supernova and will allow us to obtain the astronomical parameters for a medium rare well-known supernova remnant. Both supernovas have already been studied and we will be able to compare our results with previous studies.

In this study we will, first of all, review the explosion of supernova and its different types, the origin of cosmic rays and the principles of synchrotron radiation. A summary of assumptions and approximations will follow. Then the results will be presented with the following discussion. This study ends with a brief conclusion.

II. INTRODUCTION TO SUPERNOVA AND SUPERNOVA REMNANTS

A supernova is the final step of the evolution of a star. This process is characterized by the ejection of large amounts of mass and energy and their consequent expansion in the surrounding medium which can last weeks, even months. High quantities of energy and mass are ejected from the star, changing and interacting with the surrounding medium. Here we will describe the process of the explosion and different types of supernova. A further explanation of the evolution of the supernova remnant can be found below.

Supernovas can be classified in two main groups. Type I supernova have no hydrogen lines in their spectrum. We can differentiate types Ia, Ib and Ic. Type Ia come mostly from old and low-mass stars, leading to an almost uniform medium, with a continuum magnetic field and a uniform density. This type of supernova are, most likely, the result of white dwarfs accreting in a binary system or the merging of two white dwarfs, although the exact process that leads to the ignition of a degenerate carbon-oxygen stellar core has not yet been specified. Supernova of type Ia category are usually used for measuring the distance to their host galaxy, for they have a consistent peak luminosity fixed to their critical mass. As the interstellar medium formed within the explosion of supernova has a nearly constant density and magnetic field, they are easier to study. Types Ib and Ic (no helium lines) are associated to similar mechanisms as type II supernova but with the difference that it happens in stars that have lost their envelope earlier.

Then, we have the type II supernovas, which are originated in massive stars. When the nuclear fuel of the stellar core is exhausted, the nuclear energy, that withholds the core from collapsing, is removed and, thus, the equilibrium is broken. The core will collapse gravitationally, at a supersonic speed. Protons, under local extreme conditions, will capture electrons, releasing neutrons and neutrinos. The core collapse will be halted by the Pauli principle applied to neutrons, but the rapid collapse of the stellar core will leave the external layers of the star floating in vacuum. Sound waves will be triggered by neutrons under extreme conditions. These shock waves will reach the external layers, leading into an hydrodynamic explosion and expelling the envelope of the star, forming the supernova remnant. Although the stellar core of these stars mostly contains iron atoms, the external layers will be hydrogen rich. This is why the spectrum of type II supernova is marked with hydrogen lines.

After the supernova explosion happens, the stellar core can either continue collapsing until a black hole is formed or the neutron degeneracy will make the stellar core stable again, forming a neutron star.

A supernova releases about 10^{51}erg in kinetic energy plus the mass of the external layers expelled from the star. All this mass expelled is known as the supernova remnant and will go through four phases until it is merged with the interstellar medium.

The first phase begins with the expelling of hot plasma, forming a shock wave that will expand in the surrounding interstellar medium at supersonic speed. This is when the Sedov-Taylor phase takes part. The surrounding interstellar medium is driven by the thermal pressure of the plasma. As the remnant expands adiabatically it will lose its energy and start to cool. The ions of the plasma will recombine with free electrons, losing their energy by re-emitting radiation. At this moment, the supernova remnant propagation will decrease to subsonic velocities and become radiatively efficient, transitioning to the radiative phase, where the remnant loses part of its internal energy and is subject to instabilities, breaking into individual parts. The last phase is the dispersion one, the supernova remnant will merge with the surrounding interstellar medium.

It has to be said that the exact duration of each phase may depend on the particular remnant under study and some of the phases may be skipped or even happen at once.

III. COSMIC RAY ORIGINS AND SYNCHROTRON RADIATION PRINCIPLES

Cosmic rays are charged particles that comes from space into Earth's atmosphere. These particles, mostly protons, have relativistic energies. Cosmic rays are an important object of study because the origin of these rays is still to be determined and its understanding should help us on the comprehension of the Universe.

Cosmic rays that have energies below 100 MeV, are known to be of local flux, this meaning that they must come from the solar system, since the solar wind will shield particles with lower energy coming from outside of the solar system. For energies between 10^5 and 10^9 MeV, cosmic rays are believed to be originated in our galaxy, although there is no direct observational proof. For this energies, it is also believed that part of the cosmic rays are originated in supernova remnants through synchrotron radiation. An extragalactic component is given to the origin of cosmic rays with energies between 10^9 and 10^{13} MeV. Finally, the origin of particles with energies above 10^{14} MeV is still to be determined.

An electron moving inside an homogeneous magnetic field will emit radiation in what it is known as synchrotron radiation. As strong magnetic fields are usually found in the interior of supernova remnants it is interesting to study this type of emission coming from supernova remnants, this way we will be able to understand the physical processes that a remnant undergoes. In these fields, electrons are accelerated and thus emit continuum spectrum radiation. If the velocities of the electrons reach relativistic regimes, we will have synchrotron radiation, if not, then we have cyclotron radiation. In this study we will focus our attention to synchrotron radiation.

An electron under an homogeneous magnetic field follows an helical trajectory under the Lorentz force:

$$\vec{F} = \frac{e}{c}\vec{v} \times \vec{B} \tag{1}$$

From which we can deduce the Larmor frequency:

$$\nu_L = \frac{v \cdot \sin(\theta)}{2\pi R_L} = 2.80 \cdot 10^6 \left[\frac{B}{gauss}\right] \tag{2}$$

Where R_L is the Larmor radius. In the case of a relativistic electron, one can derive the frequency of emission as:

$$\nu_B = \frac{\nu_L}{\gamma} \tag{3}$$

Being γ the Lorentz factor. We can find the frequency at which the emission reaches a maximum and call it critical frequency. It is defined as:

$$\nu_c = \frac{3}{2}\gamma^3 \nu_B \sin(\theta) \tag{4}$$

The total radiation power emitted by a single electron is described by the equation:

$$P = \frac{dE}{dt} = \frac{2e^4B^2}{3m^2c^3}\frac{1}{\gamma^2} \tag{5}$$

But supernova remnants are formed by large amounts of material and large number of electrons, which will emit radiation in multiple wavelengths. An observer that detects radiation coming from a particular volume element is detecting the radiation emitted by a set of electrons and the radiation detected will be that of multiple wavelengths. The radiation emitted follows the rule:

$$\epsilon_\nu \propto \nu^{-\alpha} \tag{6}$$

Where $\alpha = \frac{p-1}{2}$ is known as the emission spectral index and it is a measure of the dependence of energy flux density on frequency. For synchrotron radiation we expect values for the spectral index ~ 0.7.

IV. SUMMARY OF ASSUMPTIONS AND APPROXIMATIONS

In this section we will discuss the assumptions and approximations made in order to analyze the data from the supernovas SNR 3C 391 and SN1006.

A. Assumptions for SNR 3C 391

The supernova remnant 3C 391 is known to have a turnover for frequencies below 100MHz in its integrated radio continuum spectrum. This turnover indicates free-free absorption from thermal ionized gas in the interstellar medium. The properties of the X-ray and radio emission from 3C 391 classifies it as a "mixed morphology" or "thermal composite" remnant: this means that the synchrotron radio emission is stronger in shell of the remnant while the thermal X-ray emission is stronger in its interior.

The properties of synchrotron emission of this remnant have been studied in [10], [11], [16] and [18].

The data we will analyze is digitized from [9], [13], [14] and [15]. In these studies the data is available and the error estimate is less than 20%.

In order to obtain the physical parameters and properties of this supernova remnant, we will make a weighted least-squares fit of the integrated flux to the equation: ([9])

$$S_\nu = S_{330}\left(\frac{\nu}{330MHz}\right)^{\alpha} \exp\left[-\tau_{330}\left(\frac{\nu}{330MHz}\right)^{-2.1}\right] \quad (7)$$

Where τ_{330} is the optical depth at a frequency of 330 MHz and S_{330} is the flux density also at a frequency of 330 MHz. We can estimate the free-free optical depth at other frequencies with the following equation: ([9])

$$\tau_\nu = \tau_{330}\left[\frac{\nu}{330MHz}\right]^{-2.1} \quad (8)$$

Eq.(7) allows thermal turnovers for lower frequencies and assumes a non-thermal constant power-law spectrum. This is going to be important in order to study the properties of this turnover and allow our weighted least-squares fit to show the free-free absorption turnover. A further study of the optical depth at a frequency of 74 MHz will allow us to study the origin of the thermal gas that is causing the turnover free-free absorption.

B. Assumptions for SN 1006

SN 1006 is a supernova remnant of shell type and with all physical parameters well-known. It lies above the Galactic Plane, about 550 pc ([7]), and is surrounded by a very low density environment, which suggests that the interstellar medium is free of density inhomogeneities ([1]), thus, we can assume the surrounding gas density and magnetic field to be roughly uniform. The gas density is determined by the hydrogen number density(N_H): $\rho_0 \approx 1.4 m_p N_H$ ([1]). It is a Type Ia supernova and ejects a Chandrasekhar mass $M_{ej} = 1.4 M_\odot$ ([1]).

The most precise value for the distance estimate is $d = 2.2$ kpc ([19]).

The fact that this supernova remnant is surrounded by a low density medium allowed Berezhko et al. 2012 to consider a non-linear kinetic theory of Cosmic Ray acceleration in SNR's ([4]). This theory extends the Cosmic Ray emission from supernova remnants evolution in a uniform medium to the kinetic level. It has been shown that this theory consistently explains the observational data ([4]) and we will compare our results with this study.

The data analysed is obtained from the following papers: the radio spectrum is from [2], while the X-ray spectrum is from [2] and [3]. This last set of data for the X-ray spectrum has been multiplied by a factor of 60 in order to make it consistent with the data corresponding to [3].

We will make a fit of all this data mentioned above to the following equation: ([12])

$$S_\nu = 0.017 a(\alpha) V B^{(\alpha+1)} \left(\frac{6.26 \cdot 10^{18}}{\nu(Hz)}\right)^{\alpha} Jy \quad (9)$$

Being S_ν the flux density, V the volume of the synchrotron source, B the magnetic field inside the remnant and $a(\alpha)$ a parameter that depends on the spectral index. Note that eq. (9) follows the rule $S(\nu) \propto \nu^{-\alpha}$.

Eq.(9) corresponds to the main theory of synchrotron emission. If the parameters obtained are consistent with the ones obtained by Berezhko et al. 2012, then we can be sure that the kinetic theory of cosmic rays in supernova remnants is consistent with reality.

V. RESULTS

In this section we will show the results obtained for both 3C 391 and SN 1006, this being the plot of the integrated flux and the physical parameters obtained with the fit of the corresponding equations.

A. The case of SNR 3C 391

Fig.1 shows the data obtained from the papers mentioned above with a weighted least-squares fit of eq.(7). This fit excludes the upper limit and places greater emphasis to the data with higher precision measurement, this being the data from [9], [14] and [15].

We can clearly see a turnover for frequencies below 160 MHz, as we have mentioned above. These will be discussed more deeply in the next section.

Logarithmic scales are applied in the axis of Fig.1. And thus we will have to transform eq.(7) to the following:

$$\log(S_\nu) = \log(330^{-\alpha} S_{330} e^{-\tau_\nu}) + \alpha \log(\nu) \quad (10)$$

Where we have changed the following parameter: $\tau_\nu = \tau_{330} \left(\frac{\nu}{330}\right)^{-2.1}$. We will also take $y = \log(S_\nu)$ and $x = \log(\nu)$ as the axis.

A weighted least-squares fit is then applied, finding the parameters that minimize the error:

$$E = \sum_{i=1}^{n} w_i (y_i - y(x_i))^2 \quad (11)$$

Where n is the number of data we have on our plot and w_i is the weight associated to the data.

We could also have followed another path, applying weighted least squares directly to eq.(7), finding the parameters that best fit the curve and then transform the plot into logarithmic scales.

The parameters that best fit this weighted least-squares to the transformed eq.(10) are the following:

$$\begin{aligned} \alpha &= -0.49 \pm 0.01 \\ S_{330} &= 40Jy \\ \tau_{330} &= 0.048 \end{aligned} \quad (12)$$

These results will be discussed further in the next section.

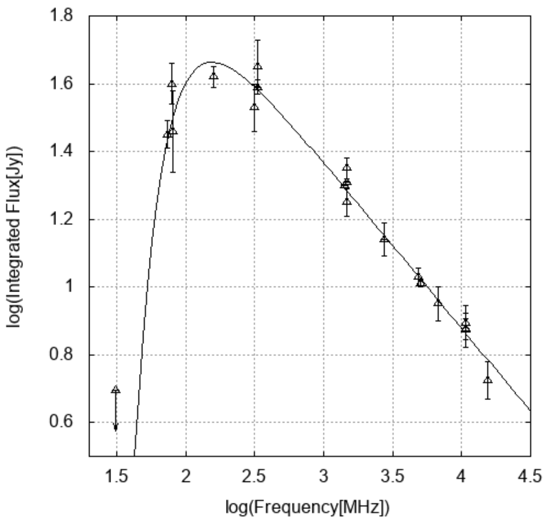

FIG. 1: Continuum spectrum for SNR 3C 391. The solid line corresponds to a weighted least-squares fit of eq.(7) excluding the 30.9 MHz upper limit. The upper limit is shown in the plot for reference. The data is obtained from [9], [13], [14] and [15].

B. The case of SN 1006

Fig.2 shows a plot of the data obtained from different papers and a least-squares fit of eq.(9) to the data.

The linear equation obtained with the fit is the following:

$$y = (-0.76 \pm 0.01) \cdot x + (3.62 \pm 0.06) \quad (13)$$

As we have applied a logarithmic scale to the axes of Fig.2, we have to transform eq.(9) to a logarithmic scale, obtaining:

$$\log(S_\nu) = \log(A) - \alpha \log(\nu) \quad (14)$$

Where $A = 0.0177 a(\alpha) V B^{(\alpha+1)} (6.26 \cdot 10^{18})^\alpha$. And, as before, we take $y = \log(S_\nu)$ and $x = \log(\nu)$ as the axis.

Comparing eq.(13) with eq.(14), we obtain the parameters that best fit the data:

$$\begin{aligned} \alpha &= 0.76 \pm 0.01 \\ B &= 30\mu G \end{aligned} \quad (15)$$

As mentioned before, the parameter $a(\alpha)$ depends on the spectral index. For the α value 0.75, $a(0.75) = 0.085$ ([17]).

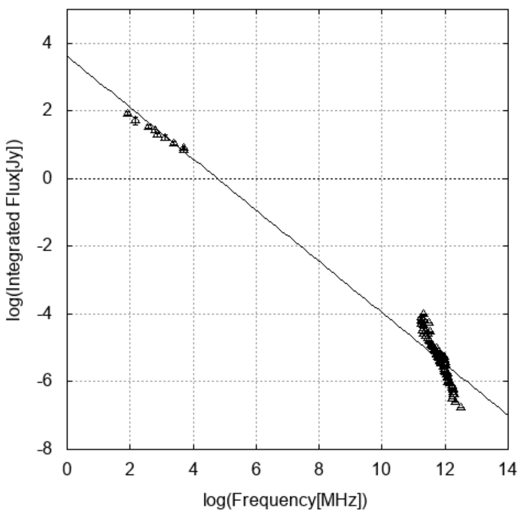

FIG. 2: Continuum spectrum for SN 1006. The solid line corresponds to a fit of eq.(9). The data is obtained from [2] and [3].

VI. DISCUSSION

In this section we will provide a full discussion and explanation of the results showed earlier. A comparison with other studies will be made.

A. Discussion for SNR 3C 391

From the obtained value $\tau_{330} = 0.048$ we can obtain the value for $\tau_{74} = 1.1$ using eq.(8), this is the optical depth at a frequency of 74 MHz. Kassim (1989b) predicted a value for τ_{74} about a factor of 2 larger than the calculated here. This is due to the fact that we have excluded the 30.9 MHz upper limit while Kassim (1989b) did not and also to the fact that we used a weighted least-squares fit. Thus, we can be sure that our estimated value is closer to the real one. Either way, in order to have a better estimate, better measurements of this upper limit should be obtained.

The turnover for low frequencies observed in Fig.1 is due to a ionized gas that causes free-free thermal absorption, but the origin of this gas is still uncertain. There are two main sources that can originate this gas: warm ionized medium and HII regions. A warm ionized medium does not account for this free-free absorption because it needs electron densities (n_e) lower than the ones estimated for this remnant. Electron densities are still to be determined, but Brogan et al. (2005) estimated an upper limit of $n_e \leq 10^3 cm^{-3}$. On the other hand, HII regions should have higher electron densities than the ones that corresponds to our optical depth at 74 MHz.

Being this two main sources discarded, Brogan et al. (2005) provides evidence for a new hypothesis: the ionized gas has its origin on the encounter of the supernova remnant shock wave with a molecular cloud that has sufficient energy to ionize the gas. It has to be said that the probability of producing observable free-free absorption with the interactions of shock waves and molecular clouds is very low. Further studies and observations in similar supernova remnants will be needed in order to determine if this hypothesis is correct.

B. Discussion for SN 1006

Berezhko et al (2012), using the kinetic theory of cosmic rays in supernova remnants obtained the following results:

$$\begin{aligned} \alpha &= 0.75 \pm 0.01 \\ B &= 30 \mu G \end{aligned} \qquad (16)$$

These results clearly coincide with the ones calculated in this study, eq.(15), and thus, we can certainly assure that the kinetic theory of cosmic rays in supernova remnants is consistent with the observed data for SN 1006.

VII. CONCLUSIONS

Fig.1 and Fig.2 show well fitted regressions for the data obtained in other studies, this meaning our study of these two supernova remnants has been consistent with realistic behaviour. Comparing our results with previous studies used as reference, we can conclude that our results are well correlated with them.

We can conclude then, that both studies for SNR 3C 391 and SN 1006 have been successful and the results are consistent with the expected values. Anyway, further studies will be necessary in order to obtain more precision and determine the origin of the ionized gas that causes free-free thermal absorption for low frequencies in the case of SNR 3C 391. For the case of SN 1006 it has been shown that the kinetic theory of cosmic rays in supernova remnants proposed by Berezhko & Völk (1997) is consistent with the observed data from SN 1006.

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