Synchrotron emission in supernova remanants

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Abstract: We have studied the spectrum of the 3C 391 supernova remnant by means of the integrated density flux. The fit of the data was made considering that the synchrotron emission is affected by free-free absorption at low frequencies. The value we obtained for the optical depth at 74 MHz is $\tau_{74} = 1.06 \pm 0.09$, showing that there is strong absorption in that region. The study from which this data was obtained, indicate that the medium responsible for the absorption could be a thermal ionized gas linked to the SNR itself.

I. INTRODUCTION

The final stage of a massive star (above $8\,\mathrm{M}_\odot$) is characterized in most cases by a high energetic explosion with a shock wave moving forward at high velocities [1]. The interaction between the material ejected and the interstellar medium surrounding the star shows radio emission, even when the explosion is no longer visible. This radio emission, which remains for some time, comes from what has been called a supernova remnant (SNR). The main source of this emission has been associated to the synchrotron emission [2].

The observations in the field of radio astronomy show spectral index variations for this emission from supernova remnants. Those changes in the power-law of the spectrum might be affected by some processes rather than the synchrotron emission itself. For some supernova remnants, it has been found that these variations in the spectral index could come from free-free absorption at low frequencies [3, 4]. Studying the characteristics of this absorption will give us information about the medium where this absorption is produced for each supernova remnant, and in addition, it will also be significant in the advance of cosmic-ray acceleration models [3].

The purpose of the present work is to study the synchrotron emission of the 3C 391 supernova remnant, considering the free-free absorption at low frequencies. Firstly there is an explanation about supernovae (SNe) and supernova remnants. Then, we make a general explanation about the synchrotron emission theory and we talk about the 3C 391 concretely. Finally, we present the results of 3C 391 spectrum, compared and discussed, with the final conclusions.

A. Supernovae

When a massive star arrives at its last stages of life, the core temperature reaches 10^{10}K, and the last element left to burn is iron [5]. This reaction consumes energy instead of releasing it, what causes the gravitational collapse of the star. Then, the core contracts at high speeds, the temperature rises and iron burns faster. The density of the core increases very rapidly, up to the point of electron degeneracy, and two possibilities can happen: if the star's mass is below the Chandrasekar's limit ($1.4\,\mathrm{M}_\odot$), the electron degeneracy pressure halts the gravitational collapse and a white dwarf is formed [6]. But for the case of very massive stars, the core's mass exceeds the Chandrasekar's limit, and the gravitational collapse continues until the temperature reaches 10^{12} K. Finally, if the stellar core's mass contains between 1.4 and $3\,\mathrm{M}_\odot$, the remnant is a neutron star. Otherwise, if the mass is higher than $3\,\mathrm{M}_\odot$, then a black hole is formed [1].

The mass of those compact remnant objects represents only a small percentage of the mass that the star had before the collapse. Once the collapse stops, the rest of the mass surrounding the star has no support. At this point, those outer layers fall onto the solid, rigid core. The temperature of the material rises to 5 billion degrees and the high pressure of the core produces a high amount of energy within a small interval of time. This results in a massive explosion that blows away most of the mass of the star, what is called a supernova (SN). More specifically, SNe with this type of explosion, which come from the gravitational collapse of massive stars, have been classified in the group of Type Ib, Ic and II [7].

The other group with which SNe are differentiated is the Type Ia, which are believed to come from the explosion of a degenerate carbon-oxygen stellar core. Although not much is known about the progenitors of these SNe, some hypotheses suggest that these explosions could come from a white dwarf in a binary system where its companion is a non-degenerate or another white dwarf [8]. Type Ia SNe are nowadays used as distance indicators and they were also of great importance in the discovery of the accelerating expansion of the Universe [5].

B. Supernova remnants

The luminosity related to the explosion of a SN is very high, due to the huge amount of energy of the explosion, that could be comparable to the energy of a galaxy. For

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this reason, when a SN occurs, it becomes easy to detect and the brightness can stay for weeks or months [9]. However, after some time, all this luminosity fades away, and only remains detectable the radio emission coming from the interaction between the shock wave of the explosion and the interstellar medium, what is called a SNR. The main source of this emission has been explained with synchrotron radiation of nonthermal electrons, and it stays detectable across the whole electromagnetic spectrum for hundreds or thousands of years [2]. Later then, the shock wave starts to decelerate by the interstellar medium and it finally disperses and merges with the surrounding gas. The detection of SNR became relevant with the discovery of a large number of objects in the galaxy that emitted in non-thermal radio and that were related to SNe that could have not been observed when the explosion occurred. The studies in the radio continuum at different frequencies have become the main mechanism for identifying new SNRs. Since SNe occur 2-3 times per century, SNRs have become a relevant source of knowledge about the population of SNe and they could provide information about the progenitors and the explosions, among others [5].

When a SN explodes about 10^{44} J of energy are released [1]. At that moment the outer layers of the star blow off forming a nebula that expands at speeds up to 5000 to 10000 km/s [10]. Several solar masses of stellar material are ejected forming a shock wave that strongly interacts with the surrounding interstellar medium, which heats up by means of magnetic turbulence and violent shocks. This could affect significantly the structure of galaxies and it is believed that could lead to the formation of new stars. The high velocities taken by the shock wave and the emission related to the SNR, are what make the difference between SNR and other types of nebulosity.

Knowing the type of SN from which originates a SNR is something complex, so it has been established a classification for SNRs depending on the radio morphology. Three classes are recognized [11]: the *shell type* SNRs, which have an appearance of a bright shell, formed of heated plasma. Another type are the *plerions*, which do not have a shell but a bright centre that often emits radiation linearly polarized and where the particles emitting synchrotron radiation are injected by a pulsar. There are also SNR which have a shell surrounding a pulsar wind nebula; those have been named as *composite* SNRs.

In general terms, the evolution of a SNR can be described in four phases [10, 11], regardless of the type of SN. Firstly, the shock wave expands at high velocities sweeping the interstellar material; at this stage the mass ejected from the SN dominates. In the second phase the mass ejected continues to dominate over the swept-up mass and radiative losses are not important. In the third phase is when energy is mostly radiated and the SNR cools down. In the last phase the velocity of the shock wave slows down as the mass ejected is comparable to the swept-up mass, and the temperature and the pressure are similar to those of the interstellar medium. At that moment the remnant becomes indistinguishable.

II. SYNCHROTRON RADIATION

Synchrotron emission has been accepted as the main radio emission source for SNRs, coming from the interaction between the ejected material by the shock wave of a SN and the interstellar medium [2]. Therefore, SNR have been basically detected through synchrotron radiation by means of radio continuum surveys.

For some SNR, variations in the spectral index have been observed, which have been associated with low-frequency absorption whose origin is not clear [3]. Studying the flux measurements, it was found that approximately 2/3 of Galactic SNRs had a spectral low-frequency turnover ($\nu \lesssim 100$ MHz) [12]. The best explanation to these turnovers for most of the SNR, has been found to be free-free absorption from dense thermal ionized gas along the line of sight.

The synchrotron radiation is emitted from non-thermal electrons with the same pitch angle moving in a radio source that contains a magnetic field [10]. The electrons, when considered as an ensemble, follow an energy density based on a power-law distribution of relativistic energies $N(E)dE = KE^{-P}$, between the range of energies $E_1 < E < E_2$ corresponding to the energy limits of the electron spectrum [2]. The radiation emitted by these electrons is linearly polarized with energies of the order of GeV. The spectrum of the emitted radiation becomes $\epsilon_\nu \propto \nu^{\frac{(1-p)}{2}} = \nu^\alpha$, where $\alpha = (1-p)/2$ is the spectral index, and for the synchrotron radiation $\alpha < 0$. This exponent becomes a useful measure of the dependence of the energy spectrum on the frequency of the radio waves observed [10].

From the energy density distribution we can calculate the emission j_ν and absorption χ_ν coefficients as a function of the frequency. From the absorption coefficient we can derive the optical depth: $d\tau_\nu = \chi_\nu ds$, where s is the optical path length [13]. Concretely the optical depth for the free-free absorption that we want to study in the present work is [12, 14]:

$$\tau_\nu = \tau_{\nu_{ref}} \left[\frac{\nu}{\nu_{ref}} \right]^{-2.1}, \quad (1)$$

where τ_{ref} is the optical depth at a reference frequency ν_{ref}. From Eq. 1 we can see that at high frequencies the source becomes optically thin ($\tau \ll 1$), while at low frequencies the source is optically thick ($\tau \gg 1$).

Then, starting from the solution of the equation of radiative transfer

$$I_\nu = \mathbb{S}_\nu \left(1 - e^{-\tau_\nu}\right), \quad (2)$$

where $\mathbb{S}_\nu = \frac{j_\nu}{\chi_\nu}$ is the source function and I_ν the intensity of the radiation measured by the observer. The observable flux of the synchrotron source is $S_\nu = \int I_\nu d\Omega \approx$

$I_\nu d\Omega$ [13], where Ω is the solid angle of the flux and we have assumed that Ω is not a function of frequency [4]. So, the flux density is [14]:

$$S_\nu = S_{ref} \left(\frac{\nu}{\nu_{ref}} \right)^\alpha e^{-\tau_\nu}, \tag{3}$$

where S_{ref} is the reference flux at the reference frequency ν_{ref}, and τ_ν is the optical depth at a frequency ν for the line of sight observed. Eq. 3 describes how at low frequencies, when the source is optically thick, it will dominate the exponential term, and the flux will rapidly rise with the frequency. At high frequencies $S_\nu \propto \nu^\alpha$, where the source is optically thin, and the flux will decrease its value as a power-law function of α. Therefore, there will be a frequency ν_m for which the flux will be maximum, and that will characterize the frequency at which the turnover occurs.

III. THE SNR 3C 391

The SNR studied in the present work, 3C 391 (also referred as G31.9+0.0) is situated in the Aquila constellation, in the Milky Way [15]. It is classified as a *mixed-morphology* SNR, also called *thermal-composite*, which is a type of SNR that has been added in the last years as the observations of X-ray satellites have evolved. These SNRs are similar to the composite: they have a shell emitting radio and a centre that emits X-ray. However, the emission originated in the centre does not come from a pulsar, but usually comes from the thermal emission from a hot plasma [11].

When studying the morphology of a SNR, it has to be considered that not all the parts are at the same phase of evolution when they are observed. Some regions may be very radiative and others may still be in a phase where the shock wave is very fast and does not radiate at all [11]. This is due to the differences in the interstellar medium, with different densities around the star that may have been modified due to the stellar wind from the progenitor. The difference of velocity during the expansion could be the reason why shell type SNRs are not perfectly circular and have a diversity of shapes [11]. It also must be considered that the shape varies depending on the orientation of the observations, as we are projecting a three-dimensional object into a two-dimensional plane [10].

Having said that, the morphology of the 3C 391 SNR is characterized by a shell with radius of 5': to the northwest it traces the shape of a partial bright circle, but to the southeast the synchrotron emission gradually faints [15]. Therefore, the shape of the shell is not perfectly circular, and it is unbounded in the southeast region [3], where the CO observations of the SNR indicate a breakout of the shock wave [16]. It has also been found some evidence that the 3C 391 SNR is interacting with a molecular cloud, proven for the presence of OH masers [3, 15]. The CO observations also support this interaction and also the hypothesis that the progenitor star exploded inside a dense molecular cloud [16].

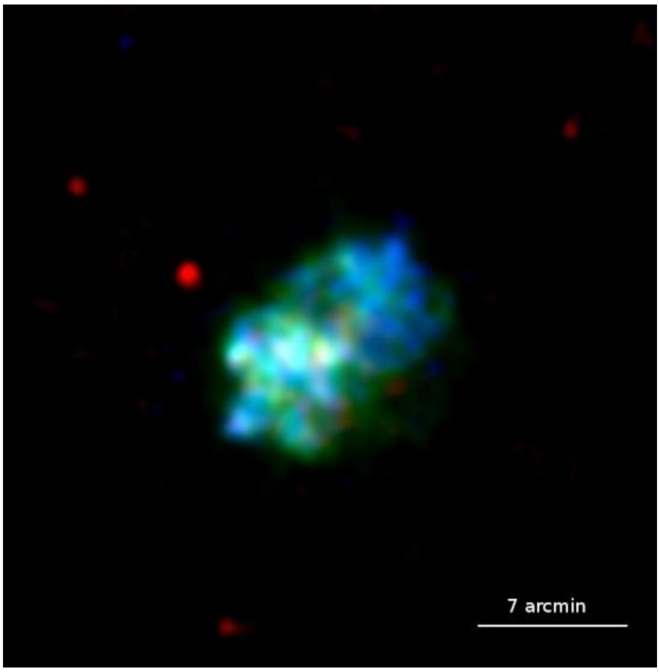

FIG. 1: X-ray image of the 3C 391 SNR taken from the XMM-Newton space observatory. For this image red=0.3-1 KeV, green=1-2 KeV and blue=2-10 KeV. Image courtesy of Marco Iacobelli and ESA/XMM-Newton.

With respect to the X-ray absorption, it varies across all the face of the SNR. Two maximums of X-ray have been observed: the brightest one is in the southeast region, heading to the faint radio extension. The other maximum, which is weaker, is in the northwest region, next to the partial bright circle [15].

The 3C 391 SNR studied in this work has been known to suffer from low-frequency absorption [3]. The observation of this SNR at low frequencies and characterizing the free-free absorption, will be very useful to identify the medium related to this absorption.

IV. ANALYSIS AND RESULTS

A. Data used

The data sets used for the present work were extracted from Fig. 2 in [3]. The sample consists of three measurements of the flux density available in the literature, chosen by the authors because they were the ones for which the error was less than 20% [3]. In addition they added three new measurements made at three different frequencies, 1465, 330 and 74 MHz, at the VLA observatory. These three values are the minimum number of measured frequencies as a prerequisite to obtain a believable value for the spectral index. The integrated flux densities are, respectively to these frequencies, 20.1 ± 0.1, 38.09 ± 0.3 and 28.1 ± 1.8 Jy, which gives a good coverage across the spectrum that may allow us to characterize the turnover.

Due to the different noise levels of the images used to obtain the flux, and taking into account the morphology of the 3C 391, it was chosen the reference frequency of 330 MHz. This way it is defined a boundary for the SNR to get comparable flux densities, even though the breakout to the southeast makes it unbounded at that part.

To determine the origin of the free-free absorption of the 3C 391, it will be useful to characterize the turnover. In order to find the optical depth and the spectral index, Eq. 3 was fitted with a weighted least-squares procedure to the data of the integrated flux. As it was said before, the reference frequency taken was 330 MHz; also, it was assumed that the spectral index, α, is constant across the radio spectrum [2]. With all this, the equation of the integrated flux results in $S_\nu = S_{330} \left(\frac{\nu}{330MHz}\right)^{\alpha} exp\left[-\tau_{330}\left(\frac{\nu}{330MHz}\right)^{-2.1}\right]$, so three parameters are searched with the fit: S_{330}, the flux density and τ_{330} the optical depth, both at the reference frequency of 330 MHz; and α the integrated spectral index.

To obtain the data sets from the integrated flux density measurements for every frequency, it was used a digitizer tool that allowed us to extract the points from the image of the graphic. Firstly the axis had to be calibrated, two points for every axis were selected and numerically defined. Then, the program allowed to select a set of points in the image and then it provided a csv file with the corresponding values. The fit was done using curve fit in python, which fits the function, in this case Eq. 3, with a non-linear least squares method to the data. The outputs returned are the three parameters indicated and its corresponding estimated covariance.

B. Results

With the representation of the data points of the flux for every frequency (triangle symbols in Fig. 2), it can be intuited that 3C 391 SNR has a low radio frequency turnover, $\nu \approx 100$ MHz, as expected. Although, there is not much data available at low frequencies, so the turnover might be seen clearly with the fit of Eq. 3.

The fit of the data to Eq. 3 is shown in Fig. 2. The best results found for the parameters are: the flux density at the reference frequency of 330 MHz is $S_{330} = 40 \pm 2$ Jy, the integrated spectral index is $\alpha = -0.49 \pm 0.02$ and the optical depth at 330 MHz is $\tau_{330} = 0.046 \pm 0.004$. The solid line, which is the data fitted with Eq. 3 replacing the parameters found, allows us to see the turnover clearer: at higher frequencies, the spectra behaves as a power-law function of the frequency like $S_\nu \propto \nu^\alpha$, where the contribution of emission is higher. Towards low frequencies, we found how the spectra turns over as a result of the effects of free-free absorption.

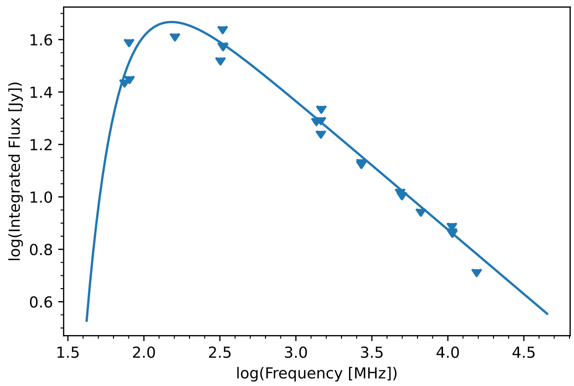

FIG. 2: Radio continuum spectrum from 3C 391. The triangles correspond to the radio flux density data that was extracted from [3] at every frequency. The solid line corresponds to Eq. 3 with the parameters obtained with the fit.

The value obtained for the spectral index, $\alpha = -0.49 \pm 0.02$, is negative and around -0.5, which is reasonable with synchrotron radiation. However, it has to be said that this value is affected by the free-free absorption, compared to an emission that does not consider absorption. To check it, we fitted the data available of the density flux for $\nu \leq 330$ MHz to $S_\nu = S_{330}\left(\frac{\nu}{330MHz}\right)^{\alpha}$, thus neglecting the effect of absorption. The result obtained was $\alpha = -0.48 \pm 0.02$. The difference is not very visible, but it is a lower value than considering the effect of absorption.

The free-free continuum optical depth at 74 MHz can be calculated with Eq. 1 and with the reference value of the optical depth τ_{330} obtained with the fit, so $\tau_\nu = \tau_{330}\left[\nu/(330\,\mathrm{MHz})\right]^{-2.1}$. The resulting value was $\tau_{74} = 1.06 \pm 0.09$. Where the error has been calculated with the propagation of error : $\delta\tau_{74} = \left[\nu/(330\,\mathrm{MHz})\right]^{-2.1}\delta\tau_{330}$. This indicates us that the free-free absorption is remarkable at these frequencies, although we do not have a lot of data from low frequencies, and specially, we do not have reliable data under 74 MHz. So, more measurements of the low-frequency region would have given us a more reliable fit. For higher frequencies, we obtained $\tau_{330} = 0.046$, indicating that free-free absorption hardly affects the synchrotron emission at these frequencies.

The results obtained for the parameters are very similar to the ones in [3]. The difference could come mainly for two reasons: first, the data sets were obtained from the image of the graphic with the digitizer; so the data used for this work may be a bit different due to the precision of the digitizer tool. Also, finding the exact centre point of every symbol was not easy, since the symbols had a big area and the data from each is in the centre. The other source of discrepancy, and maybe the most important, would be that in [3] it was used a minimization method based on a weighted least-squares fit, so the data points with less error were given more importance. For the present work, we only had the errors for the three measurements made in that article and the measurements were made giving all the data sets the same emphasis. This is what we though it would have made the main difference in the results.

The free-free absorption of the 3C 391, as commented before, was known to come from a thermal ionized gas along the line of sight at low frequencies [14]. The value obtained for the optical depth at 74 MHz agree with a strong absorption at this region of the spectrum. In [3], the absorption was spatially resolved with similar values to those we obtained in this work, as it was commented before. With the results in [3], it was found a coincidence with atomic lines that were between 12 and 18 µm and the region of free-free absorption at 74 MHz. The conclusions of this work were that the source of this ionized thermal gas linked to the absorption, is coming from the shock between the SNR and the molecular cloud that is interacting with 3C 391.

V. CONCLUSIONS

We have been able to characterize the radio continuum spectrum of the 3C 391 supernova remnant from frequencies above 74 MHz. Considering that the synchrotron emission of this SNR is affected by free-free absorption, we have been able to characterize the level of absorption. At 74 MHz the optical depth is $\tau_{74} = 1.06 \pm 0.09$, while at a higher frequency of 330 MHz, the optical depth is $\tau_{330} = 0.046 \pm 0.004$. These results confirm a strong free-free absorption at low frequencies, while at high frequencies the synchrotron emission is practically unaffected.

The value obtained for spectral index is $\alpha = -0.49 \pm 0.02$. When the free-free absorption was not considered, the fit showed a slightly smoother descent. The differences come due to the effect of the free-free absorption.

The results obtained in this work are compatible with the ones obtained in [3]. The numerical differences could come from the uncertainty when using the digitizer and above all, for the least-squares method used for the present work, that did not take into account the error of the data.

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