The supernova remnant W51C: a plausible source of galactic cosmic rays?

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Abstract.
Supernova remnants are a probable site of acceleration of particles via diffusive shock processes. High energies carried by electrons or protons are radiated into photons detectable from radio to γ rays. MAGIC has recently observed W51C, one of the most luminous galactic supernova remnants, and completed its spectrum between 50 GeV and 5 TeV. We modelled different processes for high energy photon emission of this source, and compared the predictions with the measured spectral energy distribution. It is plausible that hadrons are accelerated in the expansion front of this source, in interaction with the surrounding molecular cloud, and photons are produced in the decay of neutral mesons created in hadronic collisions.

1. Introduction
Supernova remnants are the final product of the life of a very massive star, that collapses in interaction with the surrounding molecular material originating strong blast waves, where Fermi diffusive acceleration of first order takes place [1]. The presence of ultra-relativistic particles accelerated at the shock front of the explosion is suggested by the observation of supernova remnants in radio and TeV γ rays. A spectral energy distribution of radiated photons is used to identify their emission process, connected with the nature and spectral features of their parent particles. The quest for sources of galactic cosmic rays has often indicated supernova remnants as plausible accelerators [2, 3], yet no cosmic ray astrophysics is feasible at energies below $10^{15}$ eV because of deflections, which adds interest to the indirect search for protons via γ ray emission.

2. W51C, broad-band data and new observations with MAGIC
The molecular complex W51 ($l, b = 49°, -0.38°$) hosts the supernova remnant W51C, whose shell front is in interaction with molecular clouds in the nearby star forming region W51B, forming a target of ionised material [4]; the area is filled with a magnetic field of the order of $\mu$G [5]. This work follows the recent detection of W51C with MAGIC [7], as an extended γ ray source coincident with the region of interaction between the shock and the surrounding molecular cloud. This source has been previously detected with the H.E.S.S. telescopes above 1 TeV [8], with the Fermi/LAT satellite between 200 MeV and and 50 GeV [9]; radio emission has been measured from the shell [10]. A map is shown in figure 1.
Figure 1. Relative flux map with MAGIC [7] (in colours), for energies between 300 GeV and 1 TeV (left) and above 1 TeV (right), overlaid with the region of shocked gas [6] (red dashed ellipse), and 21 cm radio continuum emission [10] (green contours). Pink contours mark the shape of the Fermi/LAT source [9].

3. Emission Processes

Given the ambient conditions of W51C, the radio emission must be explained with synchrotron radiation of electrons interacting with the ambient magnetic field, with luminosity obtained as in [11]. Three processes yield γ rays in the TeV energy range:

- **Inverse Compton scattering** of electrons on surrounding photons (cosmic microwave background, heated dust, reprocessed radiation, light of stars in the neighbourhood). The luminosity is obtained from cross section including Klein-Nishina effects as in [11], with densities for the infra-red and optical target of seed photons from a simulation of the radiation field in the galaxy [12].

- **Bremsstrahlung** of electrons on charged particles in the molecular cloud [11], as electrons, protons (from ionised hydrogen), and α particles. The luminosity for bremsstrahlung is dependent on the total target density \( \eta = \eta_e + \eta_H + \eta_{He} \), with \( \eta_e = 1.2 \eta_H \) from ionisation measurements [4] and \( \eta_{He} = 0.1 \eta_H \) off cosmic composition abundance.

- **Decays of mesons** \( (\pi^0, \eta^0) \) produced in hadronic interactions of protons or nuclei with the molecular cloud, \( pp(n) \rightarrow \pi^0(\eta^0) + X \rightarrow \gamma\gamma \).

Hadronic luminosity is obtained folding the cross section for production of meson, simulated with SIBYLL and parametrised as in [13], with its decay in flight, and is proportional to the cloud density; a nuclear enhancement factor accounts for heavier nuclei other than protons both as projectile and target.

4. Input spectra

Following the predictions of diffusive shock acceleration [1, 14], input spectra of accelerated particles are chosen in the form of a power law with either a break at \( \gamma_{br} \) (a) or a power law with exponential cut-off at \( \gamma_e \) modulated through a parameter \( l \) (b):

\[
\text{(a)} \quad S(\gamma) = \left[ \frac{\gamma}{\gamma_0} \right]^{-s} \left[ 1 + \left( \frac{\gamma}{\gamma_{br}} \right)^{\Delta s} \right]^{-1} e^{-\frac{\gamma}{\gamma_e}} \\
\text{(b)} \quad S(\gamma) = \left[ \frac{\gamma}{\gamma_0} \right]^{-s} e^{-\left(\frac{\gamma}{\gamma_e}\right)^l}
\]
Table 1. Parameters used in the modelling of the spectral energy distribution for the different scenarios.

| Model         | $a_e/a_p$ | $\Delta s$ | $E_{br}$ | $E_{cut,e}$ | $E_{cut,p}$ | $B$ | $\eta$ | $W_e$ | $W_p$ |
|---------------|-----------|-------------|----------|-------------|-------------|-----|------|------|------|
| leptonic (IC) | 1/1       | 2.1         | 10       | 50          | 50          | 2.7 | 0.1  | 14.0 | 13   |
| leptonic (B)  | 1/1       | 1.3         | 3        | 12          | 12          | 38  | 50   | 0.15 | 0.14 |
| hadronic      | 1/80      | 1.2         | 10       | 0.1         | 120         | 53  | 10.0 | 0.069| 5.8  |
| mixed         | 1/100     | 1.0         | 7        | 4           | 0.009       | 54  | 7.0  | 0.079| 5.9  |

with over-all normalisation $\gamma_0 = 10 \text{ GeV}/mc^2$ and main index $s = 1.5$ from the slope of radio data. Proton and electron normalisations, break and cut-off points are free parameters. The normalisation reflects the energy content of the explosion that goes into particles.

5. Fits
Data points must be interpolated with a linear combination of the different channels

$$\frac{1}{4\pi d^2} [a_e S_e(\gamma_e) \ast [\sigma_{IC}(\gamma_e) + \eta \sigma_B(\gamma_e) + \sigma_S(\gamma_e, B)] + a_p S_p(\gamma_p) \ast \sigma_p(\gamma_p, \eta)]$$

where $a_e/a_p$ is the electron to proton ratio, $\eta$ the particle density of the cloud, $d$ the distance of the source, $B$ the ambient magnetic field, $\gamma_e, \gamma_p$ the Lorentz factors, $S_e, S_p$ the spectra (implicitly containing breaks, indices, cutoffs), and $\sigma_i$ the various cross sections. In these models, some parameters are constrained with independent measurements: as distance, magnetic field, mass of the molecular cloud [15, 5, 6]; yield of the fits are instead those inaccessible with measurement: as normalisation and indices of input spectra, relative abundance of electrons and protons, density of the molecular cloud, amount of energy released in electrons and protons.

6. Fit results and discussion
A satisfactory fit has been obtained with an input broken power law spectrum folded with a predominant pion decay channel, with $a_e/a_p = 1:80$, and density $\eta = 10 \text{ particles/cm}^3$, shown in figure 3. A population of electrons in interaction with a magnetic field $B = 50 \mu \text{G}$ causes the observed radio emission. Parameters are summarised in table 1.

For the hadronic fit, the luminosity of W51C between 0.25 GeV and 5 TeV is $L_\gamma \approx 10^{36} \text{ erg/s}$, and the total amount of kinetic energy in electrons and protons is about 16 % of the explosion energy of the supernova. Pion production could be confirmed with the detection of neutrinos from the decay of $\pi^\pm$, whose flux is computed from the best fit proton spectrum with the same parametrisation of [13] from the best fit proton spectrum. The mixed combination of hadronic and leptonic emission shown in figure 2 (top) appears disfavoured for the high fraction of high energy electrons in the input spectrum, where cooling break is expected for electrons older than 5000 years; because it requires a fine tuning; and because parameters are unrealistic. None of the leptonic models we tried explains the data (figure 2, middle and bottom, as two examples). In particular, inverse Compton models fail to explain why the emission originates in the interaction zone between front and cloud. However, we have made some assumptions: homogeneous medium and magnetic field, and a unique population of electrons responsible for the whole emission.
Figure 2. Spectral energy distribution fit with a model dominated with a mixed hadronic and leptonic emission (top), with inverse Compton (middle) and bremsstrahlung (bottom). Data points are: radio (simple lines), Fermi/LAT (dots) and MAGIC (squares).
7. Conclusions
We have shown models for the emission of $\gamma$ rays compared with the experimental spectral energy distribution of the supernova remnant W51C, with either electrons or protons being accelerated at the source. Even in the very simple assumptions made: equilibrium, no temporal dependency, one zone, we found one model that explains the measured emission with a predominant hadronic component. We found no successful model with pure leptonic spectrum under the above assumptions. If protons are responsible for the $\gamma$ rays observed, they are a tracer of interactions between the front of the explosion and the molecular clouds; this is supported by the observation of the emission maximum in coincidence with the region of shocked gas. This result suggests that we observe ongoing acceleration of ions up to 100 TeV, and supports the hypothesis that supernova remnants are a site of acceleration of galactic cosmic particles.

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Figure 3. Spectral energy distribution fit with a model dominated with hadronic emission. Data points are: radio (simple lines), Fermi/LAT (dots) and MAGIC (squares).