

Diffusion of cosmic-rays and gamma-ray sources

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Abstract It is commonly accepted that supernova remnants (SNR) are one of the most probable scenarios of leptonic and hadronic cosmic-ray (CR) acceleration. Such energetic CR can interact with interstellar gas to produce high-energy gamma rays, which can be detected through ground-based air Cherenkov detectors and space telescopes. Here we present a theoretical model that explains the high energy phenomenology of the neighbourhood SNR IC 443, as observed with the Major Atmospheric Gamma Imaging Cherenkov (MAGIC) telescope and the Energetic Gamma-ray Experiment Telescope (EGRET). We interpret MAGIC J0616+225 as delayed TeV emission of CR diffusing from IC 443, what naturally explains the displacement between EGRET and MAGIC sources.

1 Introduction

Recently, MAGIC presented the results of observations towards SNR IC 443, yielding to the detection of a new source of γ -rays, J0616+225 [2]. This source is located at (RA,DEC)=(06^h16^m43^s, +22°31'48"), with a statistical positional error of 1.5', and a systematic error of 1'. A simple power law was fitted to the measured spectral points $dN_\gamma/(dAdrdE) = (1.0 \pm 0.2) \times 10^{-11} (E/0.4\text{TeV})^{-3.1 \pm 0.3} \text{cm}^{-2}\text{s}^{-1}\text{TeV}^{-1}$, with quoted errors being statistical. The systematic error was estimated to be 35% in flux and 0.2 in spectral index. No variability was found along the observation time (over one year). These results were confirmed by observations with the VERITAS array [24].

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MAGIC J0616+225 is displaced with respect to the position of the non-variable [32] EGRET source 3EG J0617+2238 [22]. Indeed, the EGRET central position is located directly towards the SNR, whereas the MAGIC source is south of it, close to the 95% CL contour of the EGRET detection. As [2] showed, the MAGIC source is located at the position of a giant cloud in front of the SNR, it would not be surprising if they are related, what we explore here. The EGRET flux is $(51.4 \pm 3.5) \times 10^{-8}$ ph cm⁻² s⁻¹, with a photon spectral index of 2.01 ± 0.06 . Extrapolating the spectrum of the EGRET source into the VHE regime, we would obtain a higher flux and a harder spectrum than which was observed for MAGIC J0616+225, supporting the view that a direct extrapolation of this and other EGRET measurements into the VHE range is not valid [16].

Here we present a theoretical model (see also [1, 17]) explaining the high energy phenomenology of IC 443, making focus in the displacement between EGRET and MAGIC sources. Our interpretation of MAGIC J0616+225 is that it is delayed TeV emission of cosmic-rays (CRs) diffusing from the SNR. For details, see original paper [33].

2 The SNR IC 443 in context of the model

IC 443 is an asymmetric shell-type SNR with a diameter of ~ 45 arc minutes (e.g., [15]). Two half shells appear in optical and radio images (e.g, [8, 26, 27]). The presence of maser emission at 1720 MHz at $(l, b) \sim (-171.0, 2.9)$ was reported [12]. Recently, these measurements were confirmed [23] and weaker maser sources in the region of interaction were discovered. IC 443 is a prominent X-ray source, observed with Rosat [4], ASCA [25], XMM [5, 6, 7, 9, 34], and Chandra [29, 18]. Some additional features of IC 443, relevant for our model, are:

- the age, supported to have a middle-age of about 3×10^4 yrs [10, 11, 28];
- the distance, adopted as 1.5 kpc [28, 30] (thus, 1 arcmin corresponds to 0.44 pc)
- the energy of the explosion, chosen to be 10^{51} erg, although to be conservative, we will assume that only 5% of this energy is converted into relativistic CR;
- the molecular scenario, a total mass of $\sim 1.1 \times 10^4 M_\odot$ mainly located in a quiescent cloud in front of the remnant (with linear scales of a few parsecs and densities of a few hundred particles cm⁻³) and smaller cloud(s) totalizing the remaining mass located closer to the SNR (e.g., [13, 14]).

3 Diffusion of CRs from IC 443

The spectrum of γ -rays generated through π^0 -decay at a source of proton density n_p is $F_\gamma(E_\gamma) = 2 \int_{E_\pi^{\min}}^{\infty} (F_\pi(E_\pi) / \sqrt{E_\pi^2 - m_\pi^2}) dE_\pi$, where $E_\pi^{\min}(E_\gamma) = E_\gamma + m_\pi^2/4E_\gamma$, and $F_\pi(E_\pi) = 4\pi n_p \int_{E_p^{\min}}^{E_p^{\max}} J_p(E) (d\sigma_\pi(E_\pi, E_p) / dE_\pi) dE_p$. Here, $d\sigma_\pi(E_\pi, E_p) / dE_\pi$

is the differential cross-section for the production of π^0 -mesons of energy E_π by a proton of energy E_p in a pp collision. The limits of integration in the last expression are obtained by kinematic considerations (see e.g., [31]). In these expressions we have implicitly neglected any possible gradient of cosmic-ray density in the cloud as well as in the cloud's gas number density.

The CR spectrum is given by $J_p(E, r, t) = [c\beta/4\pi]f$, where $f(E, r, t)$ is the distribution function of protons at an instant t and distance r from the source. The distribution function satisfies the radial-temporal-energy dependent diffusion equation [21]: $(\partial f/\partial t) = (D(E)/r^2)(\partial/\partial r)r^2(\partial f/\partial r) + (\partial/\partial E)(Pf) + Q$, where $P = -dE/dt$ is the energy loss rate of the particles, $Q = Q(E, r, t)$ is the source function, and $D(E)$ is the diffusion coefficient, for which we assume here that it depends only on the particle's energy. The energy loss rate are due to ionization and nuclear interactions, with the latter dominating over the former for energies larger than 1 GeV. The nuclear loss rate is $P_{\text{nuc}} = E/\tau_{pp}$, with $\tau_{pp} = (n_p c \kappa \sigma_{pp})^{-1}$ being the timescale for the corresponding nuclear loss, $\kappa \sim 0.45$ being the inelasticity of the interaction, and σ_{pp} being the cross section [19]. Aharonian & Atoyan (1996) [1] presented a solution for the diffusion equation for an arbitrary energy loss term, diffusion coefficient, and impulsive injection spectrum $f_{\text{inj}}(E)$, such that $Q(E, r, t) = N_0 f_{\text{inj}}(E) \delta r \delta(t)$. For the particular case in which $D(E) \propto E^\delta$ and $f_{\text{inj}} \propto E^{-\alpha}$, the general solution is $f(E, r, t) \sim (N_0 E^{-\alpha} / \pi^{3/2} R_{\text{dif}}^3) \exp[-(\alpha-1)t/\tau_{pp} - (R/R_{\text{dif}})^2]$, where $R_{\text{dif}} = 2(D(E)t[\exp(t\delta/\tau_{pp}) - 1]/[t\delta/\tau_{pp}])^{1/2}$ stands for the radius of the sphere up to which the particles of energy E have time to propagate after their injection. We will assume that $\alpha = 2.2$ and make use of these solutions in what follows.

3.1 Results

Fig. 1 shows the result for the γ -ray emission coming from the cloud located at the position of the MAGIC source, when we assume it lies at different distances in front of IC 443. The giant cloud mass is assumed (consistently with observations) as $8000 M_\odot$. The SNR is considered as an impulsive injector with a proton luminosity such that the energy injected into relativistic CRs is 5×10^{49} erg. The diffusion coefficient at 10 GeV, D_{10} , was chosen as $10^{26} \text{ cm}^2 \text{ s}^{-1}$, with $\delta = 0.5$. Fluxes are given for an ISM propagation in a medium of $n = 1 \text{ cm}^{-3}$. We find that clouds located from ~ 20 to ~ 30 pc produce an acceptable match to MAGIC data. Fig. 1 shows that there is plenty of room for a cloud the size of that detected in front of IC 443 to generate the MAGIC source and not a co-spatial EGRET detection (which data points are also shown in the plot). In the case of GLAST, measurement of this region will allow us to constrain the separation between the SNR and the cloud, since for some distances a GLAST detection is also predicted. The existence of a VHE source without counterpart at lower energies is the result of diffusion of the high-energy CRs from the SNR shock, which is an energy dependent process leading to an increasing deficit of low energy protons the farther is the distance from the accelerator.

To clarify our previous assertion, and since our solution to the diffusion-loss equation is a function of time, we show the evolution of the flux along the age of the SNR. In Fig. 2 we show the integrated photon flux coming from the position of the giant cloud as a function of time above 100 MeV and 100 GeV in the impulsive case. At the age of the SNR (the time at which we observe) GLAST should see a source only for the closest separations. On the contrary, the integrated photon fluxes above 100 GeV present minimal deviations, and a MAGIC source is always expected.

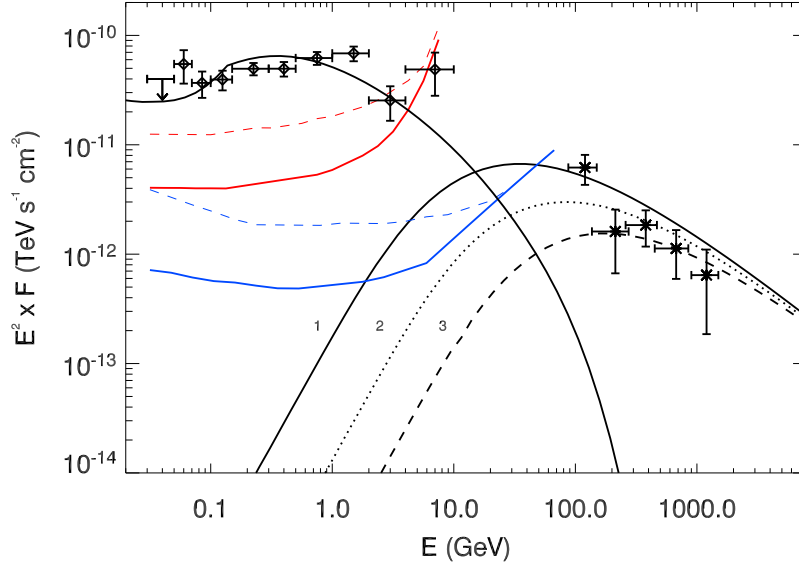


Fig. 1 MAGIC and EGRET measurement of the neighborhood of IC 443 (stars and squares, respectively) as compared with model predictions for an impulsive case. At the MAGIC energy range, the curves show the predictions for a cloud of $8000 M_{\odot}$ located at 20 (1), 25 (2), and 30 (3) pc. At the EGRET energy range, the curve shows the prediction for $\sim 700 M_{\odot}$ located at 3–4 pc. The EGRET sensitivity curve (in red) is shown for the whole lifetime of the mission for the Galactic anti-centre (solid) and for a typical position in the Inner Galaxy (dashed). The GLAST sensitivity curve (in blue) shows the 1-year sky-survey sensitivity for the Galactic North pole (solid), and for a typical position in the Inner Galaxy (dashed) [Taken from http://www-glast.slac.stanford.edu/software/IS/glast_latperformance.html].

Fig. 1 also presents the results of our theoretical model focusing in the energy range of EGRET. There, the CR spectrum interacting with a local-to-the-SNR cloud is obtained assuming an average distance of interaction of 3–4 pc. A few hundred M_{\odot} located at this distance produce an excellent match to the EGRET data, without generating a co-spatial MAGIC source. Concurrently with, e.g., [20], we find that the lowest energy data points in the EGRET range are produced by bremsstrahlung of accelerated electrons.

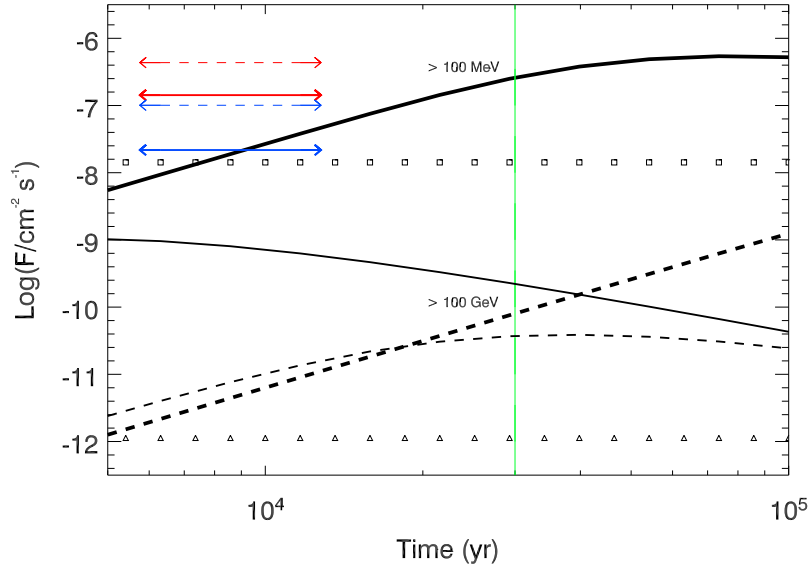


Fig. 2 Integrated photon flux as a function of time above 100 MeV and 100 GeV, solid (dashed) lines correspond to the case of the cloud located at 10 (30) pc. The horizontal lines represent the values of integrated fluxes in the case that the CR spectrum interacting with the cloud is the one found near Earth. The vertical line stands for the SNR age. EGRET and GLAST integral sensitivity, consistent in value and color coding with those in Fig. 1, are shown.

4 Concluding remarks

Here we have shown that MAGIC J0616+225 is consistent with the interpretation of CR interactions with a giant molecular cloud lying in front of the remnant, producing no counterpart at lower energies. We have also shown that the nearby EGRET source can be produced by the same accelerator, and that in this case, a co-spatial MAGIC source is not expected. In our model, the displacement between EGRET and MAGIC sources has a physical origin. It is generated by the different properties of the proton spectrum at different locations, in turn produced by the diffusion of CRs from the accelerator (IC 443) to the target. Specific predictions for future observations can be made as a result of this model. At high energies, we should see a morphological and spectral change from the position of the cloud (i.e. the center of MAGIC J0616+225) towards the center of IC 443. At a morphological level, the lower the energy, the more coincident with the SNR the radiation will be detected. At a spectral level: sufficient statistics should show that the lower the γ -ray energy the harder the spectrum is. Both predictions should show in future MAGIC II observations, and as a combination of GLAST and MAGIC data. GLAST observations, in addition, may be sensitive enough to detect the same cloud that shines at higher

energy, which ultimately will allow to determine its separation from the remnant, if the diffusion coefficient is assumed –as we showed–, or viceversa.

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