MAGIC J0616+225 as delayed TeV emission of cosmic rays diffusing from the supernova remnant IC 443

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ABSTRACT
We present a theoretical model that explains the high-energy phenomenology of the neighbourhood of the supernova remnant 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 cosmic rays diffusing from IC 443 and interacting with a known cloud located at a distance of about 20 pc in the foreground of the remnant. This scenario naturally explains the displacement between EGRET and MAGIC sources, their fluxes, and their spectra. We compare this model with others recently presented, and discuss how it can be tested with observations by the Gamma-ray Large Area Space Telescope.

Key words: gamma-rays: observations – gamma-rays: theory.

1 INTRODUCTION
Recently, the Major Atmospheric Gamma Imaging Cherenkov (MAGIC) telescope presented the results of observations towards the supernova remnant (SNR) IC 443, yielding to the detection of a new source of γ-rays, J0616+225 (Albert et al. 2007). This source is located at (RA, Dec.) = (06°16′43.′′0, +22°31′48.′′4), with a statistical positional error of 1.5 arcmin, and a systematic error of 1 arcmin. A simple power law was fitted to the measured spectral points: dN/γ(0.4 TeV) = (1.0 ± 0.2) × 10−11 cm−2 s−1 TeV−1, with quoted errors being statistical. The systematic error was estimated to be 35 per cent in flux and 0.2 in spectral index. No variability was found along the observation time (over one year). No significant tails nor extended structure was found at the MAGIC angular resolution. These results were confirmed by observations with the VERITAS array (Humensky et al. 2007). In addition, consistent upper limits were reported by Whipple (Holder et al. 2006) and CAT (Khelifi 2003).

MAGIC J0616+225 is displaced with respect to the position of the non-variable (Torres, Pessah & Romero 2001a) EGRET source 3EG J0617+2238 (Hartman et al. 1999). Indeed, the EGRET central position is located directly towards the SNR, whereas the MAGIC source is south of it, close to the 95 per cent confidence level contour of the EGRET detection. As Albert et al. (2007) 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, which we explore here. The EGRET flux is (51.4 ± 3.5) × 10−8 photon cm−2 s−1, with a photon spectral index of 2.01 ± 0.06. An independent analysis of GeV photons measured by EGRET resulted in the source GeV flux of 3.5 × 10−7 photon cm−2 s−1 at 1.7 TeV (Aharonian et al. 2000), also Gabici & Aharonian (2007) explaining the high-energy phenomenology of IC 443, focusing on 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. We compare this model with others recently presented, and discuss how it can be tested with observations with the Gamma-ray Large Area Space Telescope (GLAST).

2 THE SNR IC 443 IN THE CONTEXT OF THE MODEL
IC 443 is an asymmetric shell-type SNR with a diameter of ∼45 arcmin (e.g. Fesen & Kirshner 1980). Two half shells appear in optical and radio images (e.g. Braun & Strom 1986; Lasker et al. 1990; Leahy 2004). The interaction region, with evidence for multiple dense clumps, is also seen in 2MASS images (e.g. Rho et al. 2001). In radio, IC 443 has a spectral index of 0.36, and a flux density of 160 Jy at 1 GHz (Green 2004). Claussen et al.
(1997) reported the presence of maser emission at 1720 MHz at 
(l, b) ∼ (−171.0, 2.9). Recently, Hewitt et al. (2006) confirmed 
Claussen’s et al. measurements and discovered weaker maser 
source, observed with ROSAT (Asaoka & Aschenbach 1994), ASCA 
(Keohane et al. 1997), XMM (Bocchino & Bykov 2000, 2001, 2003; 
Bykov, Bocchino & Pavlov 2005; Troja et al. 2006) and Chand- 
dra (Olbert et al. 2001; Gaensler et al. 2006). The works by Troja, 
Bocchino & Reale (2006) and Bykov et al. (2008) summarize these 
observations. In what follows, we present some additional features 
of IC 443, relevant to our model.

(i) Age. A small (∼1000 yr) age was put forward by Wang et al. 
(1992) and followed by Asaoka & Aschenbach (1994) and Keohane 
(1997), although IC 443 is now agreed to have a middle age of about 
3 × 10^4 yr. This age has been initially advocated by Lozinskaya 
(1981) and was later consistently obtained as a result of the SNR 
evolution model (Chevalier 1999). Recent observations by Bykov 
et al. (2008) confirm that there are a few X-ray-emitting ejecta frag-
mments, a number much smaller than what should be the case in a 
younger SNR.

(ii) Distance. Kinematical distances from optical systemic veloc-
ities span from 0.7 to 1.5 kpc (e.g. Lozinskaya 1981). The assumption 
that the SNR is associated with a nearby H II region, 5249, 
implies a distance of ∼1.5–2.0 kpc. Several authors claimed that 
the photometric distance is more reliable (e.g. Rosado, Arias & 
Ambrocio-Cruz 2007), and concurrently with all other works on IC 
443, we adopt its distance as 1.5 kpc (thus 1 arcmin corresponds to 
0.44 pc).

(iii) Energy of the explosion. There is no clear indicator for E_{51}, 
the energy of the explosion in units of 10^{51} erg. Chevalier (1999) 
obtains a lower limit of 4 × 10^{50} erg, whereas lower estimations are 
provided by Dickman et al. (1992), based on Mufson et al. (1986) 
– albeit the latter assumed an age of ∼5000 yr. Lacking a strong 
reason for other numerical assumption, we will assume that E_{51} = 
1 and, although to be conservative, we will subsequently assume 
that only 5 per cent of this energy is converted into relativistic CRs. 
Reasonable differences in our assumed value of E_{51} are not expected 
to have any impact on this model.

(iv) The molecular environment. Cornett, Chin & Knapp (1977) 
and De Noyer (1979) were among the first to present detailed observa-
tions of molecular lines towards IC 443. Subsequently, Dickman 
et al. (1992), Seta et al. (1998), Butt et al. (2003) and Torres et al. 
(2003), among others, presented further analysis. These works con-
form to the current picture for the environment of IC 443: a total mass 
of ∼1.1 × 10^5 M_☉ 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$^{-3}$) that is absorbing optical and X-ray ra-
diation (e.g. Lasker et al. 1990; Troja et al. 2006), a scenario already 
put forward by Cornett et al. (1977). Dickman et al. (1992) estimated 
that 500–2000 M_☉ is directly perturbed by the shock in the northern 
region of interaction, near the SNR itself. Huang, Dickman & 
Snell (1986) found several clumps of molecular material along this 
interacting shell, with subparsecs linear scales. Rosado et al. (2007) 
found inhomogeneities down to 0.007 pc. As it is usual, we will ne-
glect these latter inhomogeneities when considering the propagation 
of CRs in the interstellar medium (ISM), that is, we thus assume a 
homogeneous medium of typical ISM density where CRs diffuse. 
The molecular mass scenario is then a main giant cloud in front of 
the SNR containing most of the quiescent molecular material found 
in the region, and smaller cloud(s) totalizing the remaining mass 
located closer to the SNR.

### 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(E_γ) = 2 \int_0^{E_{\gamma,min}} \frac{F_p(E_p)}{\sqrt{E_p^2 - m_p^2}} dE_p, 
where E_{\gamma,min} = E_{\gamma} + m_p^2/4E_p, and F_p(E_p) = 
4\pi m_p^2 \int_0^{E_p} J_\nu(E) d\sigma_{\nu\pi}(E_p, E_p) dE_p. Here, d\sigma_{\nu\pi}(E_p, E_p)/ 
dE_p is the differential cross-section for the production of π^0-mesons 
of energy E_p by a proton of energy E_p in a pp collision. For a study 
of different parameterizations of this cross-section, see Domingo-
Santamaría & Torres (2005) and Kelner, Aharonian & Bugayov 
(2006). The limits of integration in the last expression are obtained 
by kinematic considerations (see e.g. Torres 2004). In these expres-
sions, we have implicitly assumed a uniform CR density in the cloud 
as well as in the cloud’s gas number density (the size of the molecu-
lar cloud is smaller than the distance to IC 443; we therefore neglect 
the temporal, spatial changes within the molecular cloud itself; the 
whole molecular cloud becomes instantly a CR target).

The CR spectrum is given by J_\nu(E, r, t) = [ε/4πr^2]f(E, r, t) 
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 (Ginzburg 
& Syrovatskii 1964): ∂f/∂t + (∂f/∂E)r^2(∂f/∂r) + (∂f/∂E)(F_\nu) + 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 rates are due to ion-
ization and nuclear interactions, with the latter dominating over 
the former for energies larger than 1 GeV. The nuclear loss rate is 
P_nuc = E/τ_{pp}, with τ_{pp} = (n_p c σ_{pp})^{-1} being the time-scale for 
the corresponding nuclear loss, with ∼0.45 being the inelasticity of 
the interaction, and σ_{pp} being the cross-section (Gaisser 1990). 
Aharonian & Atoyan (1996) presented a solution for the diffusion 
equation for an arbitrary energy-loss term, diffusion coefficient, and 
impulsive injection spectrum J_{inj}(E), such that Q(E, r, t) = N_0J_{inj}(E)δ(t).

For the particular case in which D(E) ∝ E^1/2 and f_{inj} ∝ E^{-a}, 
the general solution is f(E, r, t) ∼ (N_0E^{-1/2}R_{diff}) \exp[−(α-1)t/r_{pp} - 
(R/R_{diff})^2], where R_{diff} = 2(D(E)[exp(β/r_{pp}) - 1]/[β/τ_{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. In case of continuous 
injection of accelerated particles, given by Q(E, r, t) = Q_0E^{-α}T(t), 
the previous solution needs to be convolved with the function 
T(t′ − t) in the time interval 0 ≤ t′ ≤ t. If the source is de-
scribed as a Heaviside function, T(t) = θ(t), Atoyan, Aharonian 
& Völk (1995) have found a general solution for the diffusion 
equation with arbitrary injection spectrum, which with the listed 
assumptions and for times t less than the energy-loss time, leads to 
f(E, r, t) = (Q_0E^{-α}/4πr^2D(E)\nu/2/√α) \int_{−∞}^{r_{diff}/c} e^{-αx} dx.

We will assume that α = 2.2 and make use of these solutions in what 
follows.

Fig. 1 shows the current CR spectrum generated by IC 443 at 
two different distances from the accelerator: 10 (solid lines) and 30 
(dashed lines) pc. The SNR is considered both as a continuous acceler-
erator with a relativistic proton power of L_p = 5 × 10^{37} erg s^{-1} 
(proton luminosity is such that the energy injected into relativistic 
CRs through the SNR age is 5 × 10^{49} erg), and an impulsive injec-
tion with the same total power (injection of high-energy particles occurs 
in a much shorter time than the SNR age). The horizontal line in 
Fig. 1 marks the CR spectrum near the Earth, so that the excess of 
CRs in the SNR environment can be seen. For this example, the 
diffusion coefficient at 10 GeV, D_{10}, was chosen as 10^{26} cm^2 s^{-1}, 
with δ = 0.5. CRs propagate through the ISM, assumed to have a
Figure 1. Current CR spectrum generated by IC 443 at two different distances, 10 (solid curve) and 30 (dashed curve) pc, at the age of the SNR. Two types of accelerators are considered, one providing a continuous injection (black) and the other providing a more impulsive injection of CRs (red). The horizontal line marks the CR spectrum near the Earth. The y-axis units have been chosen to emphasize the excess of CRs in the SNR environment.

Figure 2. MAGIC and EGRET measurements of the neighbourhood of IC 443 (stars and squares, respectively) as compared to model predictions. The top (bottom) panel shows the results for an impulsive (continuous) case. At the MAGIC energy range, the top panel shows the predictions for a cloud of 8000 M☉ located at 20 (1), 25 (2) and 30 (3) pc, whereas they correspond to 15 (1), 20 (2), 25 (3) and 30 (4) pc in the bottom panel. At the EGRET energy range, the curve shows the prediction for a few hundred M☉ located at 3–4 pc. The EGRET sensitivity curve (in red) is shown for the whole lifetime of the mission for a typical position in the Inner Galaxy, dominated by diffuse γ-ray background. The GLAST sensitivity curve (in blue) (taken from http://www.glast.slac.stanford.edu/software/IS/glast_laperformance.html) shows the one-year sky-survey sensitivity for the same position in the Inner Galaxy.

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. 3, 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. Different qualities of the accelerator (impulsive or continuous) produce a rather comparable picture. 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.

As spin-off of the constraints provided by the observed phenomenology (e.g., the molecular environment and the position of the γ-ray sources) in the setting of this model, we find that D isl should be low, of the order of 10⁹⁵ cm² s⁻¹. By varying the diffusion coefficient and studying its influence in our results, we obtain that if the separation between the giant cloud and the SNR is >10 pc, a slower diffusion would not allow sufficient high-energy particles to reach the target material; thus, the MAGIC source would not be
see that this scenario matches the observed phenomenology: the travel to its current position while accelerating particles that interact with the cloud, giving rise to the MAGIC source. We do not see that this scenario matches the observed phenomenology: the EGRET source should be on top of the current position of the pulsar and not where it actually is and, physically, it should be the result of pulsed emission (like in Vela), although pulses were not reported. The only argument supporting the latter assumption is that the flux and spectrum of 3EG J0617+2238 are similar to that of PSR 1706−44, observed by EGRET. This would apply to dozens of other EGRET sources and cannot be sustained as circumstantial evidence of physical similarity (e.g. Torres et al. 2001b; Torres et al. 2003; Reimer 2001; Romero, Benaglia & Torres 1999). In addition, the MAGIC source is generated by inverse Compton from electrons accelerated at an initial phase of the pulsar and travelling towards the cloud. Since the difference in target photon fields in the region surrounding the cloud should not be significant, and the target field should even be larger at the position of the interacting shock in the north-east, the localization and size of the MAGIC source are not explained.

Very recently, Zhang & Fang (2008) presented an alternative model for IC 443, in which a fraction of the SNR shell evolves in the molecular cloud, and other in the ambient interstellar environment, encountering different matter densities. In this model, the γ-rays observed by EGRET are mainly produced via pp interactions with the ambient matter in the clouds, as is the MAGIC source. Although this may sound similar to our model, the former is a key difference between them: in the Zhang & Fang scenario, both EGRET and MAGIC sources should be at the same position. This is a consequence of the fact that in this model, the radial dependence of the CR spectrum is not considered. As Gabici & Aharonian (2007) noted in general, and as we have seen in our IC 443 results above, an old SNR cannot confine multi-TeV particles in their shells.

5 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 centre of MAGIC J0616+225) towards the centre 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 us to determine its separation from the remnant, if the diffusion coefficient is assumed – as we showed– or vice versa.

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