CTA and cosmic-ray diffusion in molecular clouds

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Abstract. Molecular clouds act as primary targets for cosmic-ray interactions and are expected to shine in gamma-rays as a by-product of these interactions. Indeed several detected gamma-ray sources both in HE and VHE gamma-rays (HE: 100 MeV < E < 100 GeV; VHE: E > 100 GeV) have been directly or indirectly associated with molecular clouds. Information on the local diffusion coefficient and the local cosmic-ray population can be deduced from the observed gamma-ray signals. In this work we concentrate on the capability of the forthcoming Cherenkov Telescope Array Observatory (CTA) to provide such measurements. We investigate the expected emission from clouds hosting an accelerator, exploring the parameter space for different modes of acceleration, age of the source, cloud density profile, and cosmic ray diffusion coefficient. We present some of the most interesting cases for CTA regarding this science topic. The simulated gamma-ray fluxes depend strongly on the input parameters. In some cases, from CTA data it will be possible to constrain both the properties of the accelerator and the propagation mode of cosmic rays in the cloud.

Keywords: cosmic rays, gamma-ray astronomy, interstellar molecular clouds, particle diffusion
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INTRODUCTION

The physical scenario Emission in HE-VHE $\gamma$-rays is expected in spatial coincidence with molecular clouds, resulting from the hadronic interaction between cosmic-ray (CR) particles and the dense material in the cloud acting as a target. Indeed, some MCs have been detected in $\gamma$-rays in both the GeV and TeV domain [see, e.g., 1, 2, 3]. Moreover, it has been suggested that some of the still unidentified $\gamma$-ray sources might also be MCs illuminated by CRs that escaped from an accelerator located inside the cloud or in its proximity [4, 5, 6, 7]. In such cases the modeling of the emission involves the parametrization of the diffusion of charged particles. The study of this emission is extremely useful in unveiling the physics of CR sources. A more detailed study following the lines of the present contribution can be found in [8].

If a power-law energy spectrum ($J_p(E_p) = KE_p^{-\gamma}$) is assumed for the intensity of primary CRs, the resulting $\gamma$-ray spectrum due to hadronic interactions would also follow a power-law spectrum ($F(E) \propto E^{-\Gamma}$). The $\gamma$-ray spectrum reproduces the spectrum of the parent particles, at high energies. Although, if we consider energy-dependent diffusion coefficient, the CR spectrum may differ from a simple power-law near the acceleration
Here, we assumed that the source is point-like and located at the origin of the coordinate system. The acceleration and diffusion processes are computed following the approach of [5], with the appropriate solution of the diffusion-loss equation. The diffusion coefficient is assumed to depend on the CR energy only, as: \( D(E) = D_{10}(E / 10\text{GeV})^\delta \) cm\(^2\) s\(^{-1}\). We investigate the case of an accelerator at the center of a molecular cloud.

The resulting flux in \( \gamma \)-rays is mainly dependent on: diffusion coefficient and its energy dependence \((D_{10}, \delta)\); age of the accelerator; type of accelerator (impulsive/continuous); spectrum of injection \((\gamma)\); fraction of energy in input (total energy in form of cosmic rays \(W_p = \eta 10^{50}\) erg). An impulsive source of particles corresponds to the case when the bulk of relativistic cosmic-rays are released during times much smaller than the age of the accelerator itself. When the timescales are comparable, the source is referred to as a continuous injector. The total energy input is taken as \(W_p\) in the impulsive case, while the energy injection rate in the continuous case is of \(L_p = 10^{37}\) erg s\(^{-1}\), resulting in the same total input for accelerators with \(\eta = 1\) and with an age of a few hundreds of thousand years. In this scenario, a great variety of \(\gamma\)-ray spectra is expected. This can produce a variety of different GeV–TeV connections, some of which could explain the observed phenomenology [see, e.g., 11].

**CTA** The Cherenkov Telescope Array (CTA) is an international project for the development of the next generation ground-based very high energy (VHE) gamma-ray instrument. CTA will significantly advance with respect to the present generation IACTs: it will feature an order of magnitude improvement in sensitivity at the core energy range of 1 TeV, improve in its angular and energy resolution, and provide wider energy coverage, see [12]. Indeed, the array is expected to have an unprecedented sensitivity down to \(\sim 50\) GeV and above \(\sim 50\) TeV, establishing a strong link with the satellite-based operations at low energies, namely the Large Area Telescope on board the *Fermi* satellite, see [13] and water Cherenkov experiments at the highest energies [e.g, HAWC, see 14]. Both a southern and a northern hemisphere observatory are foreseen.

Detailed response functions for a proposed CTA array can be found in [15]. We use the procedure detailed there to calculate the spectral points and profiles from CTA simulated observations.

**CTA RESPONSE**

**Spectral features** A constraint on the diffusion coefficient can come from the identification of a break in the \(\gamma\)-ray spectrum integrated from the entire cloud region. The break can be related to the minimum energy that can diffuse in the entire cloud over a timescale comparable to the age of the accelerator. Equating the diffusion timescale, with the age of the accelerator, one obtains the constraints shown in Fig. 1, left, corresponding to:

\[
E_{\text{break}} = 10 \left( \frac{R_{\text{cloud}}^2}{6D_{10}\text{age}} \right)^{1/\delta} \text{GeV}.
\]  

For scenarios with galactic average diffusion (\(D_{10} = 10^{28}\) cm\(^2\) s\(^{-1}\)) and energy dependence parameter in the range \(\delta = [0.3..0.6]\), the corresponding break in \(\gamma\)-ray emission will always be at energies below the CTA energy acceptance. This is accurate for im-
pulsive accelerators. In the continuous acceleration case, new injections of high energy particles will smooth the effect of a break. At energies higher than the break given by Eq. 1, the particle spectrum will follow a power-law form composed by the slope of the injection spectrum and the energy dependence of the diffusion coefficient (i.e $\gamma + \delta$). Therefore the $\gamma$-ray emission will also show a power-law behavior, reducing the capability of constraining the parameter space from $\gamma$-ray data.

Let us assume that a molecular cloud with measured mass and distance is detected at TeV energies. Let us further assume that from multiwavelength observations we identified a possible accelerator of CRs responsible for the gamma ray emission and that an estimate of the age of that accelerator is known. In Fig. 1 we show the simulated spectra for the gamma ray emission for such an accelerator, which is assumed to be impulsive and with an age of $10^4$ years. The molecular cloud is assumed to have a mass of $M_5 = 10^5 M_\odot$ and a radius of 20 pc (hence with an average density of $n_H = 130 \text{ cm}^{-3}$) located at a distance of $d = 1 \text{ kpc}$. The other parameters are varied on a discretized grid and the corresponding observed spectrum is simulated from CTA responses. The best fitting model belonging to the parameter space grid is found along with the models with a $\chi^2$/dof not more different than unity from the best fit model. The right panel of Fig. 1 shows the case of $D_{10} = 10^{26} \text{ cm}^2 \text{s}^{-1}$, $\delta = 0.4$, $\gamma = 2.3$, $\eta = 1/3$. Thanks to the high flux reached in this case and the presence of a break, the spectrum is reconstructed easily to the intrinsic parameters, with a break at $E_\gamma \approx 2 \text{ TeV}$ and slopes $\Gamma_1 = 2.3$ and $\Gamma_2 = 2.7$ below and above the break, respectively.

**FIGURE 1.** Left Boundaries for $E_{\text{break}} > 70 \text{ GeV}$ in $\gamma$-ray (left from the boundary) for different ages of the accelerator ($10^3, 4, 5$ years are represented by the tick lines, solid, dashed, dotted curves, respectively). The thin solid line represents the boundary for an age of $10^4$ years and $E_{\text{break}} > 1 \text{ TeV}$. The point represents the parameters of the spectrum given in the right panel. Right CTA expected performances on the reconstruction of the intrinsic model for $D_{10} = 10^{26} \text{ cm}^2 \text{s}^{-1}$, $\delta = 0.4$, $\gamma = 2.3$, $\eta = 1/3$. The points are the expected spectral points from 50 hours of CTA observation time. The intrinsic spectrum is the only accepted model (see text). The expected 5 year point source sensitivity for Fermi/LAT is also given. This is calculated from the 1 year sensitivity in [13], linearly scaled with time at high energies (> 10 GeV).

**Morphology** The different scenarios can also be disentangled by investigating the morphology and extension of the emission region. The shape of those profiles depends on the parameters of the simulated scenario, an example of which is shown in Fig. 2. These profiles are easily distinguishable from each other. Extensions of the $\gamma$-ray emission depend on the parameters studied here, with some general trends. Older sources are always more extended than younger sources, as the lower energy particles will have diffused further from the center of the cloud and thus from the accelerator. Emission due
FIGURE 2. Profiles of the photon count, normalized to the respective maximum. Here we show the example of impulsive (left) and continuous (right) acceleration, $D_{10} = 10^{26} \text{ cm}^2 \text{ s}^{-1}$, $\delta = 0.5$, $\gamma = 2.2$, $\eta = 1$, at an accelerator age of $10^3$ (filled circles), $10^4$ years (open squares), and $10^5$ years (stars). Error bars are set to 10% of the count number, to mimic the expected error on the effective area for the array used in the counts determination.

to continuous accelerators will present steeper profiles due to the freshly accelerated particles in the center of the source. Faster diffusion also leads to a larger extension. The profiles in Fig. 2 are normalized to their respective maximum counts, with flux decreasing with age in the impulsive case and opposite behavior in the continuous case.

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