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PRESENTACION ORAL

Molecular clouds as reservoir of cosmic rays

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Abstract. Giant molecular clouds (GMCs) are emerging as a new population of γ-ray sources, with detections by instruments such as HESS and *Fermi*. These dense clouds are targets for cosmic rays (CRs) – locally accelerated or not –. GMCs host very young star clusters where massive star formation takes place. Some of the early-type stars are usually ejected from the clusters, becoming runaway stars, that move through the cloud. These stars develop bowshocks where particles can be accelerated up to relativistic energies. As a result, the bowshocks present radio to γ-ray emission of leptonic origin, and inject relativistic protons in the cloud. These protons diffuse in the GMC interacting with the matter via $p-p$ inelastic collisions. This gives rise to extended γ-ray sources. We present a model for the non-thermal radiation produced by locally accelerated CRs in GMCs.

Resumen. Las nubes moleculares gigantes (NMGs) están emergiendo como una nueva población de fuentes de rayos γ, con las detecciones hechas por instrumentos tales como HESS y *Fermi*. Estas nubes densas son blanco para los rayos cósmicos (RCs) – localmente acelerados o no –. Las NMGs albergan cúmulos jóvenes donde las estrellas de gran masa se forman. Usualmente algunas de las estrellas de tipo espectral temprano son eyectadas de los cúmulos, convirtiéndose en estrellas fugitivas, que se mueven a través de la nube. Estas estrellas desarrollan *bowshocks* donde las partículas pueden ser aceleradas hasta energías relativistas. Como resultado, los *bowshocks* presentan emisión en radio hasta rayos γ de origen leptónico, e inyectan protones relativistas en la nube. Estos protones se difunden en la NMG interactuando con la materia via colisiones inelásticas $p-p$. Esto da lugar a fuentes de rayos γ extendidas. Presentamos un modelo para la radiación no térmica producida por RCs localmente acelerados en NMGs.

1. Introduction

Molecular clouds (MCs) are the perfect targets for galactic cosmic rays and they contain particle accelerators. The accelerated particles in these sources add to the galactic CR population that illuminates the clouds producing γ rays (e.g., Aharonian & Atoyan 1996). GMCs are emerging as a new class of γ-ray source. Also smaller star forming regions have been detected by *Fermi*.

GMCs harbour young star clusters where massive stars form. Some young massive stars might be ejected from the clusters (Perets & Šubr 2012), becoming runaway stars (e.g., Gies & Bolton 1986). The supersonic interaction between the stellar wind with the interstellar medium (ISM) produces a bowshock (e.g., van Buren & McCray 1988). Both observational (Benaglia et al. 2010; López-Santiago et al. 2012; del Valle et al. 2013) and theoretical investigations (del Valle & Romero 2012,) support the idea that stellar bowshocks can accelerate particles up to relativistic energies.

In this work we propose that protons accelerated in bowshocks interacting with the molecular cloud matter contribute to the γ-ray emission observed in these systems.

2. The model

The gas density in MCs varies many orders of magnitude. Usually, the following profile is adopted for the density (e.g., Gabici et al. 2007): $n(R) = n_0/[1+(R/R_{\rm n})^{\beta}]$, where R is the distance from the cloud centre and $R_{\rm n}$ is the core radius. We adopt $n_0 = 10^4$ cm^{-3} and $\beta = 1$. MCs are highly magnetized structures where the magnetic field is closely related to the gas density (Crutcher 1999), i.e. $B \propto n^{\delta}$.

In this work we consider a young spherical cloud of radius $R_{\rm MC} = 50$ pc and core radius $R_{\rm n} = 0.5$ pc. This cloud hosts a massive young star cluster. We suppose that six massive stars are ejected from this cluster in random directions, in agreement with theoretical and observational evidence (Fujii & Portegies Zwart 2011; Gvaramadze et al. 2010). We consider one star of spectral type O4I (star #1), three of type O9I (stars #2, #5 and #6) and two intermediate cases (stars #3 and #4). Three of the stars have velocity $V_\star \sim 30$ km s^{-1} (stars #1-#3), two have velocity $V_\star \sim 65$ km s^{-1} (stars #3-#5), and one has $V_\star \sim 100$ km s^{-1} (star #6).

The six runaway stars produce a bowshock and inject protons in the molecular cloud as they move away from the centre. The relativistic protons diffuse in the cloud and through $p-p$ interactions with matter γ-ray emission and secondary electron-positron pairs are produced. The pairs also diffuse in the cloud and produce further non-thermal emission.

3. Calculations

The relativistic protons obey the following transport equation:

$$\begin{aligned}\frac{\partial N_p}{\partial t} &= D(E)\left[\frac{1}{R^2}\frac{\partial}{\partial R}\left(R^2\frac{\partial N_p}{\partial R}\right) + \frac{1}{R^2 \sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta\frac{\partial}{\partial\theta}\right)\right] \\ &- \frac{\partial}{\partial E}\left(P(R,\theta,E)\,N_p\right) + Q_p(R,\theta,E,t), \qquad (1)\end{aligned}$$

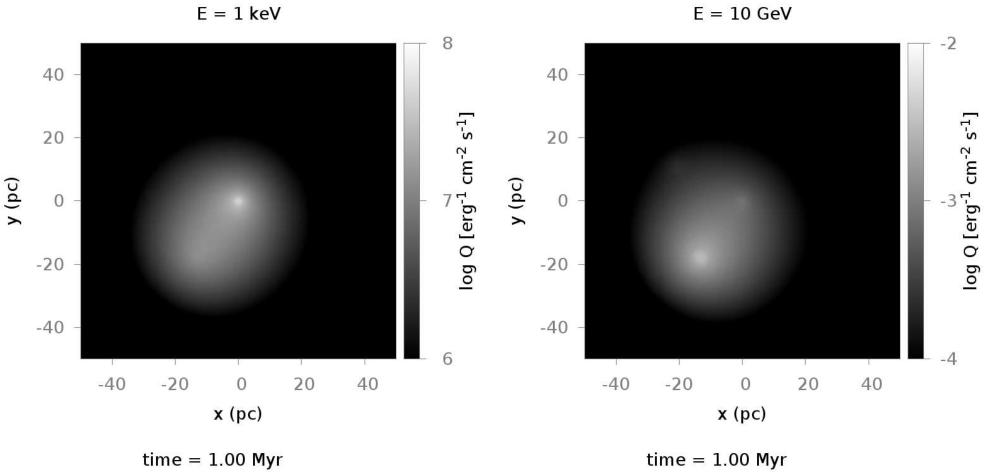

Figure 1. Total emissivity map for $E = 1$ keV (left) and $E = 10$ GeV (right), at $t = 1$ My.

where $D(\vec{r}, E)$ is the diffusion coefficient of the particles, $P(\vec{r}, E) \equiv -(\mathrm{d}E/\mathrm{d}t)$ is the radiative energy loss rate and $Q_p(\vec{r}, E, t)$ is the injection function. Here we adopt a scalar diffusion coefficient $D(E) = 10^{26}\,(E/10\,\mathrm{GeV})^{1/2}$ cm^2 s^{-1} (e.g., Gabici et al. 2007). The dominant losses for protons are $p-p$ inelastic collisions (Aharonian & Atoyan 1996). The $e^{\pm}$ pairs follow a similar transport equation, but the injection function depends on the $p-p$ interactions (Kelner et al. 2006) and the radiative losses are dominated by synchrotron emission. We simultaneously solve the transport equations for protons and pairs using a finite volumes method.

We calculate the non-thermal emission as a function of time and position on the cloud. For protons we calculate the emission produced by neutral pion decay and for the $e^{\pm}$ pairs we calculate the synchrotron emission (see e.g., Aharonian 2004).

4. Results

In Fig. 1 we show the emissivity maps, integrated along the line of sight, for two energies: 1 keV and 10 GeV, after 1 Myr of the ejection. The different properties of the injectors produce an important spatial anisotropy in the emissivity.

The Fig. 2 shows the spectral energy distribution (SED) at $t = 1$ Myr, integrated over the nuclear region (left) of the cloud and integrated over the whole cloud (right). We also consistently compute the background CR contribution to the non-thermal SED for two values of CR density (light and dark gray lines).

5. Conclusions

The level of protons and secondary pairs, under some assumptions, dominate over the CR sea that penetrates the MC. The γ-ray luminosity produced by the

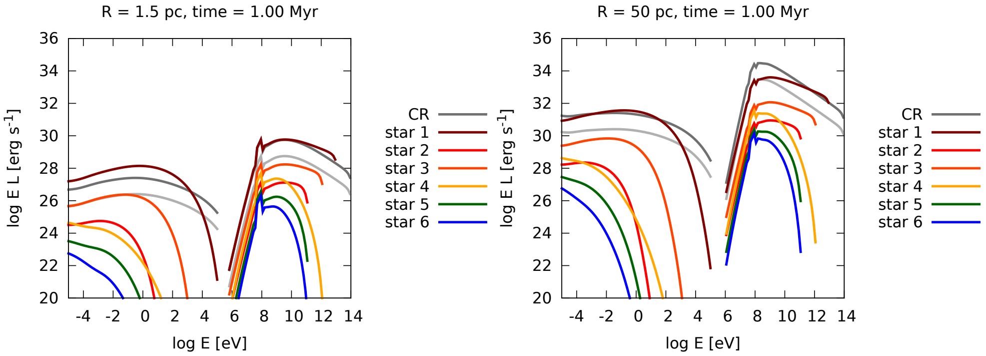

Figure 2. Integrated spectral energy distribution from the cloud core (left) and from the whole cloud (right). The background CR contribution is also shown (see the text for further details).

protons reaches values of $\sim 10^{34}$ erg s^{-1}. The non-thermal emission from radio to X-rays is significant, with luminosities of almost 10^{31} erg s^{-1}. However, in a MC thermal emission might dominate in many regions of this energy range.

The results we present here are very sensitive to the diffusion coefficient and to the ambient CR density. Both quantities are not very well known. However, the forthcoming γ-ray observatory, Cherenkov telescope array (CTA), is expected to obtain solid constraints on the particle diffusion coefficient (e.g., Pedaletti et al. 2013).

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