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Studies of nonthermal emission of illuminated molecular clouds

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Abstract. The interaction of cosmic rays with molecular clouds produces nonthermal emission mainly at high energies. These clouds are gamma ray sources when they are illuminated by cosmic rays. Following this scenario, we investigated the interaction of background cosmic rays and of an injection source, a supernova remnant, with molecular clouds with emphasis on gamma-ray production. Firstly, we compared the time-scales of the competing physical processes involved in order to obtain the most relevant ones. As a result, we obtained that the diffusion is the dominant process in the particles' transport. Then, we performed the calculation of the transport of cosmic rays when interacting within the clouds and the nonthermal radiation produced. Then, we numerically solved the transport equation for protons and electron-positron pairs in a 3D grade: 2 spatial dimensions plus 1 in energy. We obtained emission maps and spectral energy distributions in the whole electromagnetic spectrum.

Resumo. A interação de raios cósmicos com nuvens moleculares produz emissão não térmica, principalmente nas altas energias. Essas nuvens são fontes de raios gama quando elas são iluminadas por raios cósmicos. Diante desse cenário, investigamos a interação dos raios cósmicos de fundo e de uma fonte injetora, um remanescente de supernova, com nuvens moleculares, com ênfase na produção de raios gama. Primeiro, comparamos escalas temporais dos principais processos físicos envolvidos, a fim de obtermos os mais relevantes. Como resultado, temos que a difusão é o processo dominante no transporte das partículas. Em seguida, realizamos o cálculo do transporte dos raios cósmicos quando interagindo dentro da nuvem e da radiação não térmica produzida. Depois, resolvemos numericamente a equação de transporte para prótons e pares elétron-pósitron em uma grade 3D: duas dimensões espaciais mais uma na energia. Nós obtivemos mapas de emissão e distribuição espectral de energia em todo o espectro eletromagnético.

Keywords. Gamma Rays: ISM – ISM: Clouds – Cosmic Rays

1. Introduction

Galactic cosmic rays (CRs) are deflected in the magnetic fields of the interstellar medium, therefore the best way to study their sources is through the nonthermal emission they produce. The perfect targets for CRs in the Galaxy are molecular clouds (MCs), as they are very dense and form large complexes. The main goal of this work is the investigation of the interaction of CRs within MCs. This research involves the calculation of the transport of CRs and the radiation when interacting inside these dense clouds (e.g., Gabici & Aharonian 2007). We consider two cases: the background *cosmic-ray sea* and the case of a supernova remnant (SNR) as a relativistic particle source (e.g., Gabici, Aharonian & Blasi 2007).

2. The Model

In order to compare the physical processes involved in this scenario we compute the time-scales of the spatial diffusion, advection, proton-proton inelastic collisions and dynamical time of the system as a function of the particle energy. Through all this work we assume that the CRs are protons. We follow the model by Gabici, Aharonian & Blasi (2007). The results are shown in Figure 1. For these calculations we assumed a uniform cloud of density $n = 200\,\mathrm{cm}^{-3}$, magnetic field $B = 10\,\mu\mathrm{G}$, and size $r = 50\,\mathrm{pc}$. For the diffusion we use $D(E) = D_0(E/10\,\mathrm{GeV})^{-0.5}$, with $D_0 = \chi\, 3 \times 10^{27}\,\mathrm{cm}^2\,\mathrm{s}^{-1}$. We conclude that diffusion dominates and that advection can be neglected.

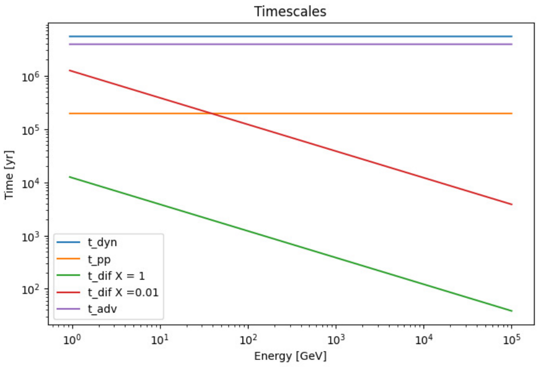

Figure 1: Timescales of the relevant physical processes as a function of the proton kinetic energy.

The interactions of the CRs within the MCs are contained in the transport equation, in this case in spherical coordinates:

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

where N_p is the proton energy distribution. The term $P(r,\theta,E)$ refers to the radiative losses. $Q_\mathrm{p}(r,\theta,E,t)$ is the particle injection; for the case of a source it is given by:

$$Q_p(r,\theta,E,t) = Q_0\,E^{-\alpha}\,\delta^3(\overrightarrow{r} - \overrightarrow{r_s}), \qquad (2)$$

here the term Q_0 is the normalization related to the power injected in particles and $\overrightarrow{r_s}$ is the SNR's position relative to the cloud. For the case of the cosmic-ray sea, $Q_\mathrm{p}(r,\theta,E,t) \equiv 0$.

In the case without a injection source, we demanded the proton distribution to be equal to the observed Galactic CRs distribution at the cloud boundary. The flux of locally observed CRs is given by (e.g., Simpson 1983):

$$J_\mathrm{CR}^\mathrm{gal}\,(\mathrm{E}) = 2.2\left(\frac{\mathrm{E}}{\mathrm{GeV}}\right)^{-2.75}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}\,\mathrm{GeV}^{-1}. \qquad (3)$$

In order to solve the transport equation for protons and electron-positron pairs[1] we use the modular code Tandil (see, del Valle, Romero & Santos-Lima 2015). Consequently, it is possible to obtain the resulting luminosity of the produced emission by the high-energy protons and pairs in the MC as a function of time. In the case of no injection source we are interested steady state of the system, and the problem has spherical symmetry.

We adopted here a cloud with density and magnetic field radial decaying profiles, with values at the core $n_{\rm core} = 10^4\,{\rm cm}^{-3}$ and $B_{\rm core} = 10\,\mu{\rm G}$, respectively. The cloud size was of $R = 50\,{\rm pc}$ with $r_{\rm core} = 10\,{\rm pc}$. For the diffusion we used $D_0 = 3 \times 10^{25}$, this is a slow regime, expected in such a dense and turbulent environment. In the case of the SNR, the injector was located at $r = 40\,{\rm pc}$ and we assumed an injection power $P = 10^{36}\,{\rm erg\,s}^{-1}$, and a power-law energy distribution with index $\alpha = -2.2$, as expected in a diffusive shock acceleration process. We computed the transport of particles for $t = 1$ Myr.

3. Results

The Figure 2 show a map of the proton (left panel) and pairs (right panel) distributions within the MC for the fixed energy E = 10 GeV for the case without a source, i.e. only protons from the background diffuse into the cloud. The obtained distribution maps for the case of the SNR are shown in Figure 3, also for $E = 10$ GeV.

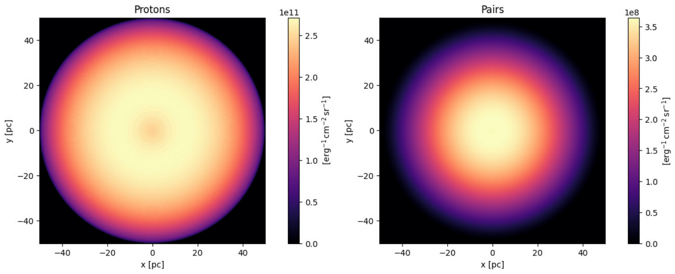

FIGURE 2: Proton (left) and pairs (right) distribution map for $E = 10$ GeV - for the background CRs at a steady state.

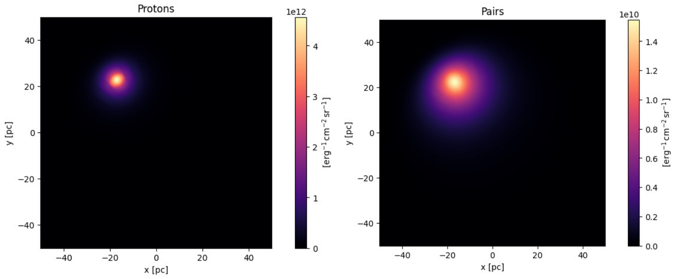

FIGURE 3: Same as Figure 2, but for the case of a source of CRs within the cloud at $r = 40\,{\rm pc}$, for $t = 1$ Myr.

The obtained nonthermal spectral energy distribution (SED) from the total cloud is shown in Figure 4. The gamma-ray emissivity and the synchrotron radiation are shown for both cases: background CRs and SNR.

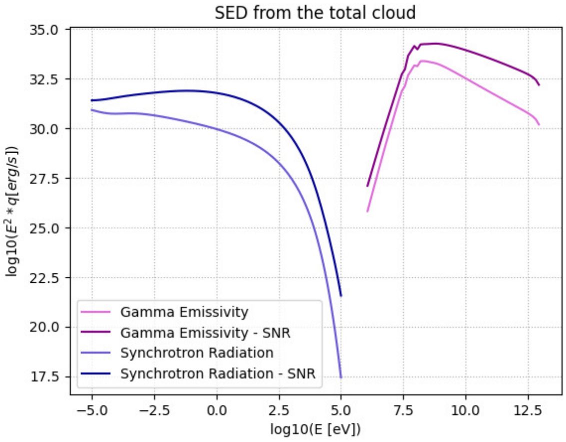

FIGURE 4: Gamma-ray emission and synchrotron radiation produced from the whole cloud, as a function of the photon energy for both cases studied: background and source of CRs.

4. Conclusions and Future Work

Concerning the particle distribution inside the cloud for the case of no injection source, the protons and electron-positron pairs are not uniformly distributed inside the cloud. The presence of a source of particles increases the number of particles by a factor of ∼ 20. This enhancement is spatially confined, near the injector. The position of the SNR inside the cloud is important in the production of gamma rays and pairs.

Regarding the luminosity, we can observe that the gamma-ray emission dominates over the synchrotron and that the obtained spectral shape is different in both situations here analyzed.

As for future prospects, we plan to apply our model to specific sources. Also, we will study the observability of the produced nonthermal emission by current and future gamma-ray observatories.

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[1] The pairs are created when a high-energy proton (i.e., a CR) collides with the clouds' material, trough the *proton-proton* inelastic collision process.