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Molecular cloud as multimessenger source

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Abstract. Cosmic rays are relativistic particles of galactic and extragalactic origin, primarily composed of protons, alpha particles, heavier nuclei, and a small fraction of electrons. In the interstellar medium, cosmic rays interact with molecular clouds, producing particles such as gamma rays and neutrinos, which characterizes the cloud as a multimessenger source. Cosmic rays are the only ionizing agents capable of penetrating the dense regions of molecular clouds and maintaining a balance between the coupling of the gas to the magnetic field against the gravitational force. Thus, we investigate the mechanisms of cosmic-ray interactions with molecular clouds in order to understand the physical processes occurring inside the cloud, such as the energy deposited in different regions and also the production of secondary particles. For this, the Geant4 software is used, which simulates the interaction of radiation with matter via Monte Carlo method.

Resumo. Raios cósmicos são partículas relativísticas de origem galática e extragalática, compostas majoritariamente por prótons, partículas alfas, núcleos mais pesados e uma pequena fração de elétrons. No meio interestelar os raios cósmicos interagem com nuvens moleculares produzindo partículas como raios gama e neutrinos, o que caracteriza a nuvem como fonte multi-mensageira. Os raios cósmicos são os únicos agentes ionizantes capazes de penetrar as regiões densas das nuvens moleculares e manter um equilíbrio entre o acoplamento do gás junto ao campo magnético contra a força gravitacional. Assim, investigamos os mecanismos de interação de raios cósmicos com nuvens moleculares afim de compreender os processos físicos que ocorrem no interior da nuvem como a energia depositada em diferentes regiões e também a produção de partículas secundárias. Para isso é utilizado o software Geant4 que simula a interação da radiação com a matéria via método de Monte Carlo.

Keywords. molecular cloud – gamma rays – neutrinos

1. Introduction

Cosmic rays are highly energetic charged particles originating both within and beyond our galaxy, reaching Earth with an energy spectrum spanning from 10 MeV to above 10^{20} eV. This energy spectrum can be described by a power-law distribution, $dN/dE \propto E^{-\alpha}$, indicating physical processes of non-thermal particle acceleration. Molecular clouds in the vicinity of cosmic-ray accelerators act as dense targets for cosmic-ray interactions, producing gamma ray and neutrino emissions that enable the identification of cosmic-ray sources Montmerle (1979). The irradiation of molecular clouds by cosmic rays results in various physical and physico-chemical changes, ranging from deposited energy that heats the cloud and the formation of particles (intranuclear cascades) to molecular dissociation and the eventual formation of new species Padovani et al. (2009).

The gamma-ray emissions are crucial for understanding the role of cosmic rays in the evolution of molecular clouds and the distribution of energetic particles in the interstellar medium Castro et al. (2013). Additionally, neutrino production can also occur in regions of intense star formation. These particles are challenging to detect due to their weak interaction with matter Roy et al. (2024). Detecting neutrinos from regions near molecular clouds would help identify locations of extreme astrophysical activity and events such as supernova explosions and mergers of compact objects.

2. Methodology

Using Geant4[1], a toolkit that enables the simulation of radiation passing through matter, we modeled a molecular cloud consisting of 13 layers with concentric spherical structures representing the physicochemical conditions of a molecular cloud of 4.8 pc (see Figure 1). The density varies as $r^{-1.2}$, where r is the average radius of each layer. The index value -1.2 was adopted as an average index for the density distribution profile of molecular clouds (the modeling is based on Pazianotto et al. (2021)).

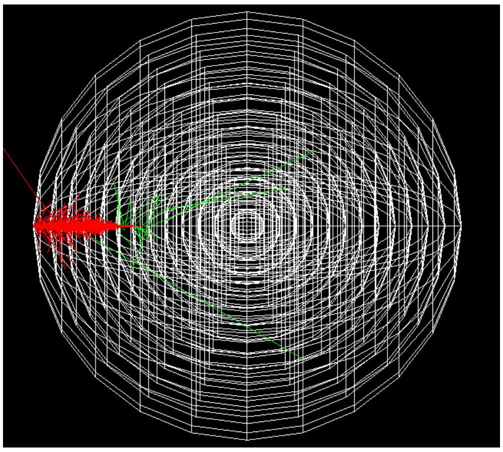

Figure 1. Geant4 visulization of an electron beam (solid red line) inciding perpendicularly to the molecular cloud plane, producing gamma rays and electron neutrinos (solid green lines).

The chemical composition of the modeled molecular cloud corresponds to a mixture of H_2 and carbonaceous grains (expressed in terms of H and C atoms). The grains have a density of 2.1 g cm^{-3} and a radius of 50 nm. Each cloud layer is composed of 99.83 % H_2 atoms and 0.17 % C atoms (the dust-to-gas mass ratio is approximately 1/100). This ratio in the Milky Way

[1] https://geant4.web.cern.ch/

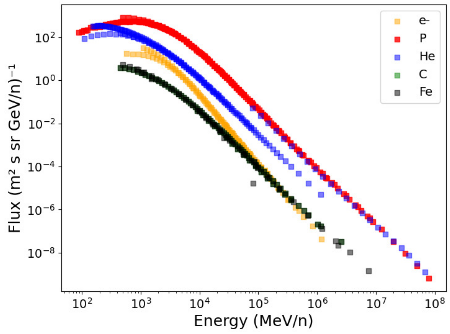

Figure 2. Primary cosmic-ray spectra measured by different space missions.

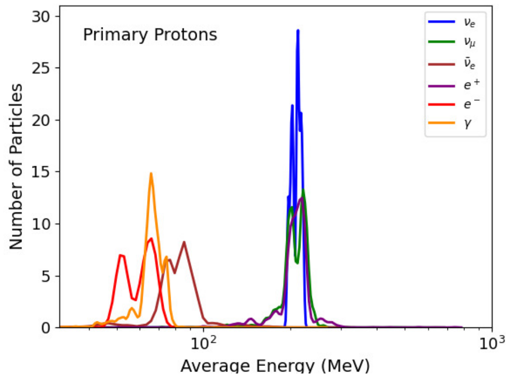

Figure 3. Secondaries emerging from the molecular cloud for proton as primary cosmic rays.

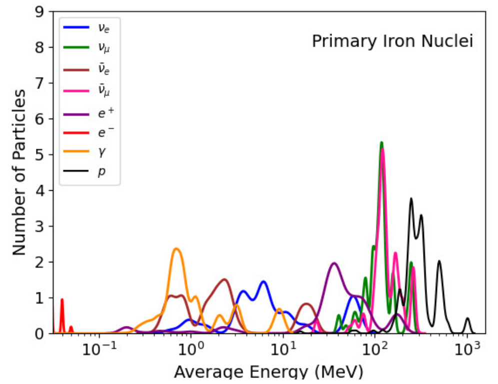

Figure 4. Secondaries emerging from the molecular cloud for iron nuclei as primary cosmic rays.

has been established as roughly 1:100 in the diffuse interstellar medium Bohlin et al. (1978), with typical sizes below 1 μm in molecular clouds Pazianotto et al. (2021).

We used the cosmic-ray flux of various chemical compositions (Fe, C, e -, p, He) obtained from several space missions (AMS-02, CALET, Fermi-LAT, CREAM, PAMELA, TRACER, DAMPE, and BESS-Polar II), which are available in the Cosmic Ray Database[2]. The observed cosmic-ray fluxes (see Figure 2) were used as input in Gean4 simulation.

3. Results

One of the main findings is the fact that molecular clouds can be potential candidates for the production of multimessenger particles, including gamma rays and neutrinos. Figures 3 and 4 present the distributions of particles that emerged from the molecular cloud for protons and iron nuclei as primary cosmic rays. The most likely particles analyzed include e -, e +, gamma rays (from π^0 decay), and muonic and electronic neutrinos (resulting from $\pi^\pm$ and $\mu^\pm$ decay).

For electrons as primary cosmic rays, a significant number of gamma rays emerge from the cloud, whereas for iron nuclei as primaries, muonic neutrinos and their respective antineutrinos prevail. The energy of the secondary particles depends on the primary cosmic-ray energy, as well as the density and composition of the molecular cloud. The information gathered is sufficient to suggest that molecular clouds are source candidates of ν_e, $\bar{\nu}_e$, ν_μ, $\bar{\nu}_\mu$ and gamma rays.

4. Conclusions

Heavier cosmic rays, such as iron nuclei, deposit more energy into molecular clouds, while lighter particles, such as electrons and protons, have a lesser impact. This behavior directly influences the production of secondary particles, such as neutrinos and gamma rays, making molecular clouds promising candidates for multimessenger sources.

The use of Geant4 has proven to be an essential tool for modeling the complex interactions of cosmic rays with interstellar matter, enabling advances in understanding fundamental processes within molecular clouds. The results underscore the significance of these structures as natural laboratories for studying the origin and propagation of energetic particles in space.

Dense gas regions irradiated by cosmic rays play a crucial role in high-energy astrophysics, particularly in identifying sources of neutrinos and gamma rays. Furthermore, emissions from molecular clouds provide a unique opportunity to probe the cosmic-ray energy spectrum in our galaxy, linking observations of diffuse emissions to extreme astrophysical phenomena such as supernova explosions and interactions of galactic cosmic rays.

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[2] https://tools.ssdc.asi.it/CosmicRays/