Intrusion of Cosmic-Rays into Molecular Clouds Studied by Ionization, the Neutral Iron Line, and Gamma-Rays

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Abstract

Low-energy (~MeV) cosmic-rays (CRs) ionize molecular clouds and create the neutral iron line (Fe I Kα) at 6.4 keV. On the other hand, high-energy (≳ GeV) CRs interact with the dense cloud gas and produce gamma-rays. Based on an one-dimensional model, we study the spatial correlation among ionization rates of gas, 6.4 keV line fluxes, and γ-ray emissions from a molecular cloud illuminated by CRs accelerated at an adjacent supernova remnant. We find that the spatial distributions of these three observables depend on how CRs intrude the cloud and on the internal structure of the cloud. If the CR intrusion is represented by slow diffusion, the 6.4 keV line should be detected around the cloud edge where ionization rates are high. On the other hand, if CRs freely stream in the cloud, the 6.4 keV line should be observed where gamma-rays are emitted.

1. Introduction

Supernova remnants (SNRs) are considered a main source of cosmic-rays (we consider protons as CRs) in the Milky-way. Some SNRs are surrounded by molecular clouds. γ-ray emissions have been observed from such molecular clouds. While the gamma-rays are created via pp-interaction, only CRs with energies of $E \gtrsim$ GeV can exceed the threshold of the interaction.

In this study, we show that the 6.4 keV neutral iron line (Fe I Kα) and the ionization rates of dense clouds can be used to study the distribution of CRs with MeV energies and to discuss the intrusion of CRs into the clouds (Fig. 1).

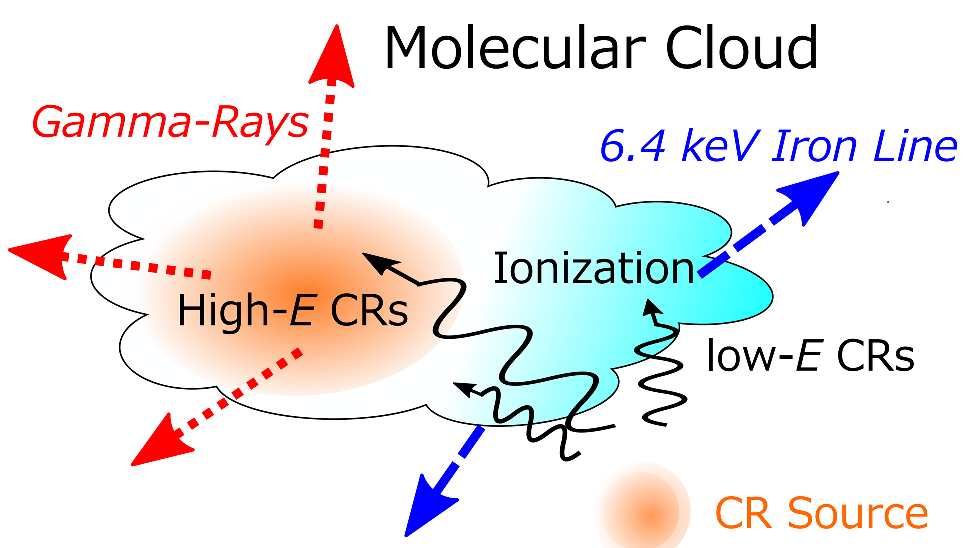

Figure 1. Schematic figure of CR intrusion into a molecular cloud. Low-E CRs ionize the gas and produce the iron line, and high-E CRs produce γ-rays.

2. Models

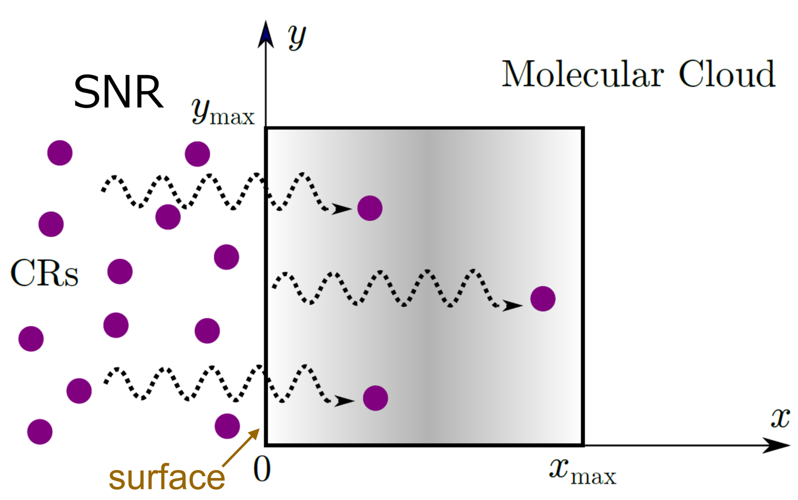

Figure 2. Schematic figure of our model.

A molecular cloud is in contact with an SNR. We consider two possibilities for the propagation of CRs: a diffusive case and a free-streaming case. For the former, we solved a one-dimensional (Fig. 2) diffusion-advection equation.

$$\frac{\partial f}{\partial t} = \frac{\partial}{\partial x}\left(D\frac{\partial f}{\partial x}\right) - v\frac{\partial f}{\partial x} - \frac{1}{p^2}\frac{\partial}{\partial p}(\dot{p}p^2 f)$$

The diffusion coefficient is given by

$$D(p) = 1\times 10^{28}\chi\frac{v_p}{c}\left(\frac{pc}{10\ \mathrm{GeV}}\right)^{\delta}\left(\frac{B}{3\ \mu\mathrm{G}}\right)^{-\delta}\ \mathrm{cm^2\ s^{-1}}$$

where δ =1/3 and χ=0.01 (slow diffusion), which may be realized by growth of magnetic fluctuation by CRs. We also considered the intrusion when CRs freely stream in the cloud, which may be realized when the fluctuation damps by neutral gas particles.

3. Results

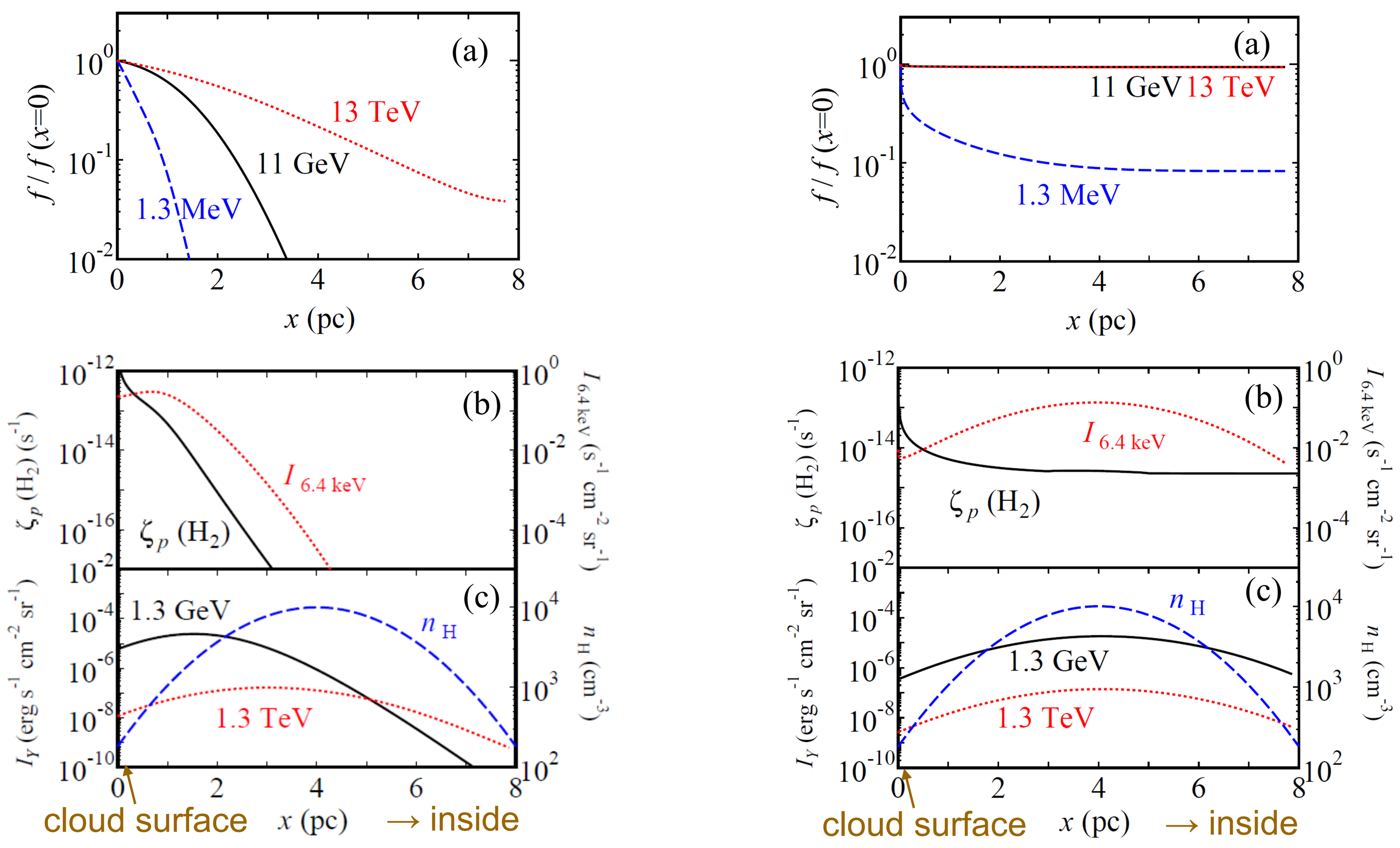

Figure 3. Left: slow diffusion, Right: free streaming. (a) CR distribution, (b) intensity of the iron line ($I_{6.4\mathrm{keV}}$), and ionization rate (ξ_p), (c) γ-ray intensity.

We assume that the cloud is in contact with a supernova remnant (SNR) that supplies CRs at x=0 (Fig. 2). In the diffusive case (Fig. 3, left), CRs with higher energies can penetrate deeper inside the cloud (Fig. 3 left a). The ionization and the iron line mainly produce by CRs with energies of ~0.01 MeV and ~10 MeV, respectively. The gamma-rays produced by CRs with those of ≳ GeV. Thus, their intensities are distributed accordingly (Fig.3 left bc). The iron line should be observed in the outskirts of the cloud as it is as the highly ionized region. In the free-streaming case, on the other hand, the iron line should be detected in the gamma-ray bright region (Fig. 3 right).

4. Comparison with observations

So far, 3 SNRs (W28, IC443, and W51C) have been studied on the 3 observables (ionization rates, the iron line, and γ-rays). We have compared our predictions with the spatial distribution of the observables. We found both diffusive and free-streaming cases. The *XRISM* satellite will reveal which case is dominant in the near future.

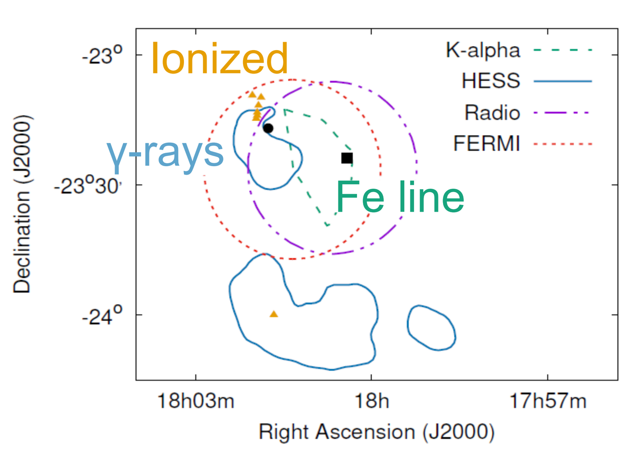

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Figure 4. Distributions of ionized regions, the iron line, and γ-ray intensities around SNR W28. The iron line region is shifted from γ-ray emitting region, which supports diffusive case.