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Research Paper

Ionization of protoplanetary disks by galactic cosmic rays, solar protons, and supernova remnants

Ryuho Kataoka [a,b,*], Tatsuhiko Sato [c]

[a] National Institute of Polar Research, 10-3 Midori-cho, Tachikawa, Tokyo, 190-8513, Japan
[b] SOKENDAI, 10-3 Midori-cho, Tachikawa, Tokyo, 190-8513, Japan
[c] Japan Atomic Energy Agency, Shirakata 2-4, Tokai, Ibaraki, 319-1195, Japan

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A B S T R A C T

Galactic cosmic rays and solar protons ionize the present terrestrial atmosphere, and the air showers are simulated by well-tested Monte-Carlo simulations, such as PHITS code. We use the latest version of PHITS to evaluate the possible ionization of protoplanetary disks by galactic cosmic rays (GCRs), solar protons, and by supernova remnants. The attenuation length of GCR ionization is updated as 118 g cm^{-2}, which is approximately 20% larger than the popular value. Hard and soft possible spectra of solar protons give comparable and 20% smaller attenuation lengths compared with those from standard GCR spectra, respectively, while the attenuation length is approximately 10% larger for supernova remnants. Further, all of the attenuation lengths become 10% larger in the compound gas of cosmic abundance, e.g. 128 g cm^{-2} for GCRs, which can affect the minimum estimate of the size of dead zones in protoplanetary disks when the incident flux is unusually high.

1. Introduction

Galactic cosmic rays (GCRs) are the major ionization sources of the present terrestrial atmosphere. One of the best-tested GCR-induced air shower simulation codes is PHITS: Particle and Heavy Ion Transport code System (Sato et al., 2013). The code has been employed in GCR-induced air shower simulation for developing the PARMA model, which comprises numerous analytical functions with parameters whose numerical values were fitted to reproduce the PHITS simulation results (Sato, 2015). PHITS has also been used in solar flare-related air shower simulation for developing WASAVIES: WArning System for AVIation exposure to Solar energetic particles (Sato et al., 2014; Kataoka et al., 2014a, 2015). Recently, Kataoka et al. (2014b) showed an extreme example of PHITS's applications to the expected radiation dose at the Earth during the catastrophic collision of the heliosphere with a nearby supernova remnant as simulated by Fields et al. (2008).

A star formation may also be affected by the extremely enhanced ionization of a molecular cloud due to a supernova remnant, via changing both the ambipolar diffusion time and the distribution of dead zones in the accretion disk (Fatuzzo et al., 2006), and can also be an important target of PHITS simulations. In a "dead zone" of protoplanetary disks (Gammie, 1996), presumably near the midplane where ionization level is the lowest, the turbulence resulting from magneto-rotational instability (Balbus and Hawley, 1991) cannot participate for the angular momentum transport, which has been regarded as the key to the evolution of protoplanetary disks themselves, dust grains, and therefore the origin of planets (Sano et al., 2000; Okuzumi and Hirose, 2012). Turner and Drake (2009) suggested that a variety of dead zones can exist in protoplanetary disks, considering the ionizations from enhanced GCRs or from enhanced solar protons. In fact, T Tauri stars can be magnetically more active than the present Sun to truncate the accretion disk by the dipole-like magnetic field (Shu et al., 1994), and solar protons from the young Sun can have a significant impact on the ionizations of the protoplanetary disk, which can be comparable with those by GCRs.

The most popular model of GCR-induced ionization profile for protoplanetary disks was proposed 35 years ago by Umebayashi and Nakano (1981), hereafter UN81, and the attenuation length of GCR-induced ionization was estimated as 96 g cm^{-2} for a pure hydrogen gas. The purpose of this study is to examine and update the attenuation length for a pure hydrogen gas and also for a

* Corresponding author. National Institute of Polar Research, 10-3 Midori-cho, Tachikawa, Tokyo, 190-8513, Japan.
E-mail address: kataoka.ryuho@nipr.ac.jp (R. Kataoka).
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compound gas of cosmic abundance using the latest version of PHITS code. We discuss the possible range of the variable ionization profiles due to other energetic particles with softer or harder spectra, such as solar protons from the young Sun and also energetic protons generated at supernova remnants, respectively. A new model of proton spectra of the young Sun is also proposed for this purpose, as a function of magnetic moment of the central star and accretion rate.

2. Method

We consider cylindrical areas with homogeneous gas density of 10^{10} and 10^{14} cm^{-3}. Two different compositions are selected, i.e. pure hydrogen gases and compound gases of cosmic abundance with 75% hydrogen and 25% helium in the mass ratio. The height and radius of the cylindrical areas are fixed to 1500 g cm^{-2}. We assume that the GCRs or solar protons with different energy spectra (Fig. 1) are perpendicularly incident to the cylindrical gas at the center of the flat top surface. The deposition energy is then scored as a function of the depth from the front surface.

The latest version of PHITS, v.2.82 with the recommended nuclear reaction models and data libraries such as JAM (Nara et al., 2000), INCL4.6 (Boudard et al., 2013) and EGS5 (Hirayama et al., 2005), were employed in the simulation. The decay of neutrons is indispensable to be considered in the simulation because of the extremely large scale of the simulation phase space, up to 10^{12} km for the lowest density case. However, PHITS 2.82 cannot consider the decay of neutrons because the mean life of neutron is so long in comparison to the time scale of conventional particle transport simulation. In this study we therefore implement the new function to consider the neutron decay with the mean life time of 887 s. This function will be available in the forthcoming version of PHITS. Note that the decay of other particles such as pions and muons can be taken into account in the default setting of PHITS 2.82.

Energy spectra of GCRs at the present Earth position are given as a reference in this study by the model developed by Matthia et al. (2013), as a function of solar modulation index W. We use the minimum ($W = 0$) and maximum ($W = 200$) modulation indices to see the range of the weakest and strongest current solar activities, respectively. The same GCR spectrum as used in UN81 is also used as another reference. Note that Cleeves et al. (2013) suggested T-Tauliosphere modulation model, which consider stronger GCR modulation than the maximum modulation assumed in this paper. The absolute values of the all energy spectra adopted in this study are normalized to give the same flux of UN81 at 10 GeV, as shown in Fig. 1.

Energy spectra of solar protons are modeled as a power law up to the maximum energy E_{max}, assuming a shock acceleration at Alfven radius of the young Sun, as a function of shock Mach number m (see Appendix for the detailed formulations). We assume $m = 10$ as a strong shock (power law index $\gamma = -2.0$ and $E_{max} = 190$ GeV), and also consider $m = 2.0$ as a weak shock ($\gamma = -10/3$ and $E_{max} = 38$ GeV). Additionally, we consider an extreme shock spectrum without the maximum energy ($\gamma = -2.0$ and $E_{max} = 1.0$ TeV) to see the hardest possible example in our framework, assuming a nearby supernova remnant. The extreme "supernova" shock spectrum may also be a useful setting for considering the star formation associated with supernova remnants as discussed by Fatuzzo et al. (2006).

3. Results and discussions

3.1. Comparison with the UN81 model

Fig. 2 shows the ionization rates for the gas densities of 10^{10} and 10^{14} cm^{-3}, using the same UN81 spectrum. These data are obtained from the doses per unit fluence calculated by PHITS in Gy cm^2, multiplied with $\Phi\Omega/e\rho W_0$, where Φ is the integrated particle flux at

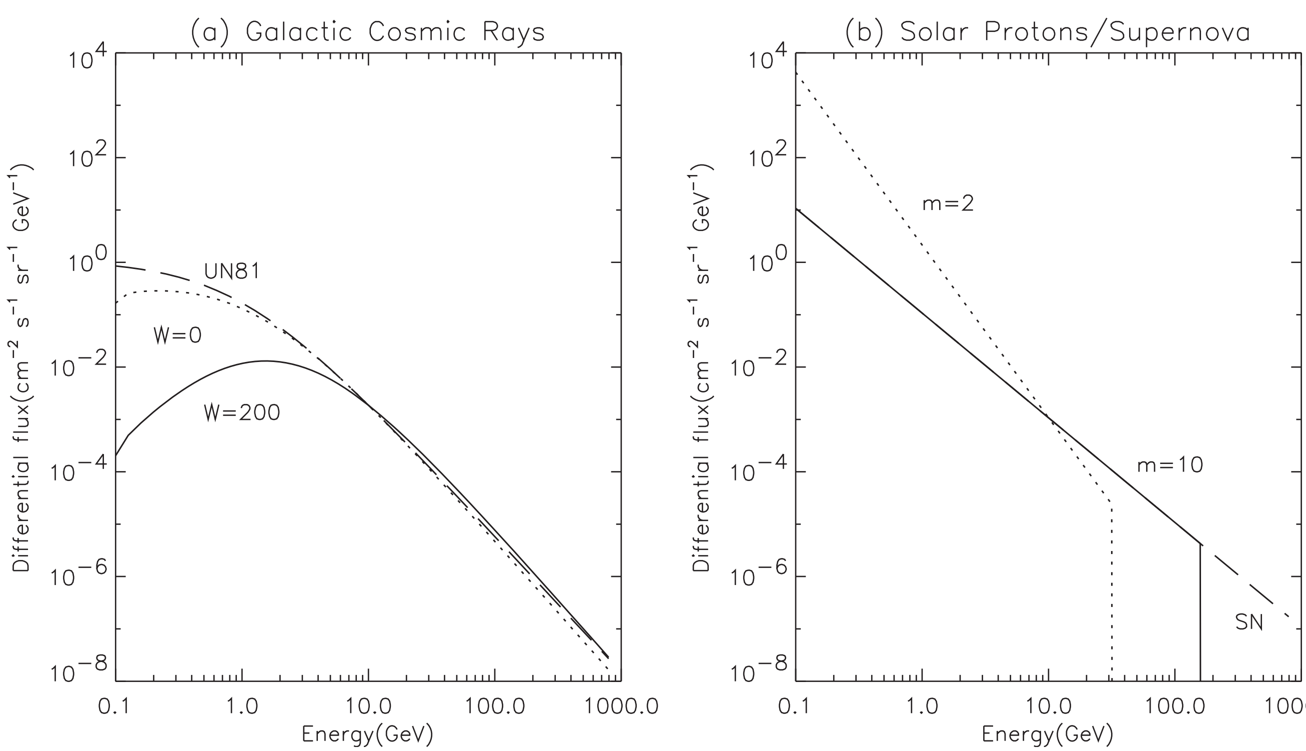

Figure 1. Assumed energy spectra for (a) galactic cosmic rays of weak ($W = 0$) and strong ($W = 200$) solar activities and of UN81 model, and for (b) solar protons of weak shock ($m = 2$), strong shock ($m = 10$), and of "supernova" extreme shock. All of the differential flux values are normalized with those at 10 GeV.