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# Spectrum and ionization rate of low-energy Galactic cosmic rays

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**ABSTRACT**

We consider the rate of ionization of diffuse and molecular clouds in the interstellar medium by Galactic cosmic rays (GCRs) in order to constrain its low-energy spectrum. We extrapolate the GCR spectrum obtained from *PAMELA* at high energies ($\geq$200 GeV nucleon$^{-1}$) and a recently derived GCR proton flux at 1–200 GeV from observations of gamma-rays from molecular clouds, and find that the observed average Galactic ionization rate can be reconciled with this GCR spectrum if there is a low-energy cut-off for protons at 10–100 MeV. We also identify the flattening below a few GeV as being due to (a) decrease of the diffusion coefficient and dominance of convective loss at low energy and (b) the expected break in energy spectrum for a constant spectral index in momentum. We show that the inferred CR proton spectrum of $\Phi \propto E_{\rm kin}^{-1.7\pm0.2}$ for $E_{\rm kin} \leq$ few GeV is consistent with a power-law spectrum in momentum $p^{-2.45\pm0.4}$, which we identify as the spectrum at source. Diffusion loss at higher energies then introduces a steepening by $E^{-\alpha}$ with $\alpha \sim 1/3$, making it consistent with high-energy measurements.

**Key words:** ISM: clouds – cosmic rays – ISM: molecules.

## 1 INTRODUCTION

The interaction of cosmic rays (CRs) with interstellar material is a powerful probe of the spectrum, and consequently of the origin, of Galactic CR (GCR). CR particles ionize the interstellar atoms and molecules, and the ionization rates can be inferred from the abundance studies of different species, such as $H_3^+$ (McCall et al. 2003; Indriolo et al. 2007; Goto et al. 2008). They also spallate interstellar nuclei such as C, N and O to create light-element isotopes of Li, Be and B (Reeves, Fowler & Hoyle 1970; Meneguzzi, Audouze & Reeves 1971). CRs also excite nuclear states of certain nuclei and produce gamma-ray lines; they also produce gamma-rays from pion decay after interacting with interstellar protons (Meneguzzi & Reeves 1975; Issa & Wolfendale 1981).

These interactions provide a method of probing the spectrum of GCRs at low energy where direct observations suffer from the effect of solar modulation. Since these interactions depend on known cross-sections and an assumed extrapolation of the CR spectrum to low energies, such studies have yielded valuable constraints on the low-energy CRs. The observed light-element abundances have been used in this regard (e.g. Meneguzzi et al. 1971; Vangioni-Flam et al. 1996; Kneller, Phillips & Walker 2003), as well as gamma-ray lines (Meneguzzi & Reeves 1975; Ramaty, Kozlovsky & Lingenfelter 1979; Cassé, Lehoucq & Vangioni-Flam 1995; Fields et al. 1996; Tatischeff & Kiener 2004), in addition to ionization rates (Hayakawa, Nishimura & Takayanagi 1961; Spitzer & Tomasko 1968; Nath & Biermann 1994; Webber 1998).

The observed determination of hydrogen ionization rate in diffuse interstellar medium (ISM) $\zeta^{\rm H}$ ranges between a few $\times 10^{-17}$ s$^{-1}$ and a few $\times 10^{-16}$ s$^{-1}$, based on the abundance measurements of various species such as OH and HD (Black & Dalgarno 1977; van Dishoeck & Black 1986; Federman, Weber & Lambert 1996). These inferred rates, however, depend strongly on various assumptions such as that of the background ultraviolet radiation field. It has been shown that a CR spectrum with a low-energy cut-off ∼50 MeV can explain the observed rates (Spitzer & Tomasko 1968; Nath & Biermann 1994). For ionization of molecular hydrogen, the standard conversion rate of $1.5\zeta^{\rm H_2} \approx 2.3\zeta^{\rm H}$ (Glassgold & Langer 1974) then predicted $\zeta^{\rm H_2} \leq 10^{-17}$ s$^{-1}$. The observed value of $\zeta^{\rm H_2}$ in molecular cloud (MC) cores, however, ranged between $10^{-17}$ and $10^{-15}$ s$^{-1}$ (Caselli et al. 1998), with the values in high-density cloud cores being $\zeta^{\rm H_2}$ a few $\times 10^{-17}$ s$^{-1}$ (van der Tak & van Dishoeck 2000).

Recently, a high-ionization rate ($\sim$4–6 $\times$ $10^{-16}$ s$^{-1}$) has been determined in diffuse clouds through the abundance measurement of $H_3^+$ (McCall et al. 1998; McCall et al. 2003; Indriolo et al. 2007; Goto et al. 2008). The simplicity of reactions involving $H_3^+$ makes this a robust determination. There appears to be a range of observed

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molecular ionization rates from diffuse clouds with low molecular content to that in dense clouds. Gerin et al. (2010) and Neufeld et al. (2010) found an ionization rate of 0.6–2.4 × $10^{-16}\,\mathrm{s}^{-1}$ in diffuse clouds with low molecular content ($H_2/H \leq 10$ per cent), whereas Indriolo et al. (2010) have found an ionization rate as large as $\sim 2 \times 10^{-15}\,\mathrm{s}^{-1}$ near the supernova remnant (SNR) IC 443. The contrast between the low-ionization rate in MC cores and the high rate in diffuse clouds can be reconciled by either postulating that CRs are inhibited in dense MCs by some plasma processes or that there is an additional low-energy component in the diffuse component of CRs which cannot penetrate the dense cloud cores (Indriolo, Fields & McCall 2009; Padovani, Galli & Glassgold 2009).

Recently, Neronov, Semikoz & Taylor (2012; hereafter NST12) have determined a spectrum of GCR protons down to a kinetic energy of ∼1 GeV, using the observed gamma-ray emission from nearby MCs at the Gould belt, and normalizing the flux at high energy (≥200 GeV) to the flux determined by *PAMELA*. They found that in order to explain the observed gamma-ray spectrum, the CR proton spectrum requires a spectral break around 9 GeV, below which it becomes shallow. The low-energy shape of the spectrum derived by NST12 is interesting with regard to the above discussion of high-ionization rate $\zeta^{H_2}$ in that the low-energy flux is substantially enhanced above the flux extrapolated from high energies. NST12 interpreted the shape of the low-energy spectrum as being due to the interaction of CRs with interstellar material in the last $\sim 3 \times 10^7$ yr while traversing a distance of ∼1 kpc from the Gould belt. In this Letter, we suggest another possibility, that the break arises from a combination of (a) the source spectrum being a power law in momentum and (b) the dominance of convective loss over diffusion at low energies. We then extrapolate this spectrum down to a low-energy cut-off below which we assume the CR flux to be negligible, and compare the predicted ionization rate with the average observed Galactic ionization rate.

Becker et al. (2011) recently considered the ionization rate by CRs in MCs close to SNRs which are believed to accelerate CRs. They extrapolated the theoretically predicted CR spectrum from shock acceleration mechanism, down to MeV energies, and calculated the predicted ionization rate as a function of a low-energy cut-off, which they used to predict abundance of (and emission-line strengths from) species such $H_2^+$. In a related paper, Schuppan et al. (2012) considered a few MCs associated with SNRs, and determined the CR spectrum from the observed gamma-ray spectrum, assuming a break at 1 GeV and then going down to a low-energy cut-off of the order of 30–100 MeV. Then they calculated the corresponding ionization rate in the MCs, which they found to be larger than the Galactic average in a few cases.

Our line of approach is different from these. We adopt the spectrum of CRs determined by NST12 as the average GCR spectrum, and calculate the average ionization rate, which we compare with the observed average ionization rate and discuss the possible low-energy cut-off for the average GCR flux. Since this CR spectrum is different from the ones adopted by recent authors, with a spectral break at $E_\mathrm{b} \sim 9$ GeV and with a steeper spectral index between $E_\mathrm{b}$ and ∼200 GeV, the corresponding ionization rate cannot be easily translated from other works. Our goal here is therefore to consider the average GCR flux and compute its ionization rate and compare it with the ionization rate in MCs *not* associated with SNRs.

## 2 SPECTRUM OF LOW-ENERGY GCR

The CR spectrum derived by NST12 has a spectral index $\Gamma_2 = 3.03^{+0.37}_{-0.18}$ above a break at $E_\mathrm{b} = 9^{+3}_{-5}$ GeV and a spectral index $\Gamma_1 = 1.9^{+0.2}_{-0.9}$. The authors state that including a component of bremsstrahlung to the gamma-ray emission reduces the low-energy spectral index to $\Gamma_1 = 1.7 \pm 0.2$. The inverse-Compton contribution is likely to be negligible if there is no star-forming region in the MC. Gabici, Aharonian & Casanova (2009) have estimated that inverse-Compton loss becomes significant only if there is an OB association with a total output of $\sim 4 \times 10^{33}\,\mathrm{erg\,s}^{-1}$ located in the MC. In the case of MCs considered by NST12, there are no SNRs associated with them, and we assume that inverse-Compton loss is not significant. After inferring the spectral indices from gamma-ray emission, NST12 normalize the CR spectrum with the high-energy measurement ≥200 GeV with *PAMELA* (Adriani et al. 2011).

We note that the CR spectrum inferred at high energy ($E_\mathrm{kin} \geq 10$ GeV) by NST12, with spectral index of $3.03^{+0.37}_{-0.18}$, is consistent with or close to that measured by different experiments. For example, *PAMELA* finds a spectral index of ∼2.85 for protons in the range 80–230 GeV (Adriani et al. 2011). However, *AMS* measured an index of 2.78 ± 0.009 at 10–200 GeV (Aguilar et al. 2002), *BESS* an index of 2.732 ± 0.011 at 30toafew hundred GeV (Haino et al. 2004) and *CREAM* measured an index of ∼2.66 ± 0.02 between 2.5 and 250 TeV (Yoon et al. 2011).

The expected spectrum of CRs from diffusive shock acceleration is a power law in momentum ($p$) (e.g. Bell 1978; Drury 1983; Blandford & Eichler 1987, and references therein). Although at high energies the corresponding spectral index in energy is the same as that for momentum, since $E \propto pc$, a break is to be expected there in the energy spectrum at a few GeV, with a different spectral index for the low-energy CRs, for which one should use $E_\mathrm{kin} = \sqrt{p^2c^2 + m^2c^4} - mc^2$ instead of the approximation of $E \sim pc$. We show in Fig. 1 that a spectrum of $\Phi(p) \propto p^{-2.45}$ shows a break in the spectrum in kinetic energy at a few GeV, with the low-energy spectral index being ∼1.7, and recovering the index of 2.45 at higher energies. The figure shows that the energy spectrum changes at $\sim \log_{10}(E_\mathrm{kin}/m_\mathrm{p}c^2) \leq 0.6$, or $E_\mathrm{kin} \leq 3.7$ GeV, which lies in the range of measurement of NST12 ($E_\mathrm{kin} \geq 2$ GeV), and is comparable to the lower ($1\sigma$) error margin of the break energy $E_\mathrm{b}$ ($9_{-5}$ GeV).

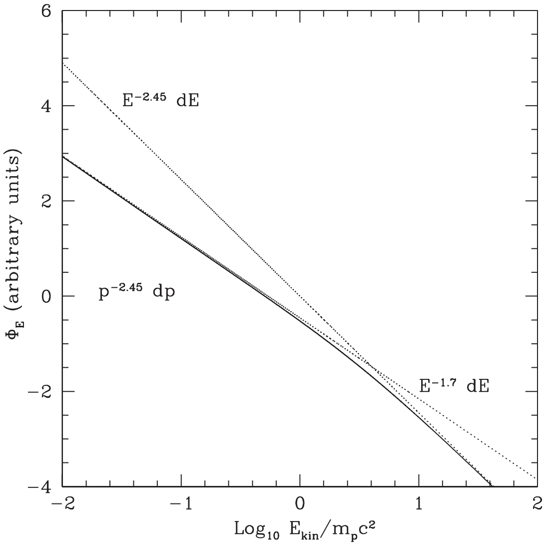

**Figure 1.** CR proton energy spectra are shown with fluxes in arbitrary units, against kinetic energy in the units of rest-mass energy. The solid lines show a spectrum with constant power law in momentum (with an index −2.45), and the dotted lines show the asymptotic behaviour at low- and high-energy ends.

Our choice of the spectral index is aimed at recovering the inferred index of 1.7 at low energies by NST12. The uncertainty in the inferred spectral index ($-1.7 \pm 0.2$) translates into an uncertainty in the momentum spectral index of $-2.45 \pm 0.4$.

We also note that the diffusion coefficient of CRs in the ISM is thought to be energy-dependent, and this energy dependence steepens the observed CR spectrum compared to the source spectrum. For protons ($Z = 1$), the diffusion coefficient at high energies scales as $D \propto \upsilon\, p^{\alpha}$, where $\alpha$ depends on the nature of turbulences which scatter the CRs; $\alpha \sim 1/3$ for Kolmogorov-type spectrum of turbulence (e.g. see section 2 in Ptuskin et al. 2006). At low energies, the diffusion coefficient becomes independent of energy below an energy of ~3 GeV (for protons, with $Z = 1$), as suggested by the observed ratios secondary to primary nuclei (Ptuskin et al. 2006). However, as Biermann et al. (2001) have suggested, convective transport is likely to become more dominant than diffusive ones since it is faster, at energies $\leq$ few GeV nucleon$^{-1}$. In other words, the mode of CR transport likely changes at $E_{\rm kin} \sim$ few GeV nucleon$^{-1}$, with convection dominating at low energies and diffusion at high energies. Therefore, if we identify $p^{-2.45\pm0.4}$ as the source spectrum, then (a) at low energies (a few GeV nucleon$^{-1}$), diffusion loss does not steepen the spectrum, and we get a spectral index of $-1.7 \pm 0.2$ in kinetic energy, and (b) the high-energy spectrum will steepen by $d\gamma \sim 1/3$, rendering an index $\sim -2.8 \pm 0.4$, consistent with the high-energy measurements as mentioned above, especially the *AMS* data. Also, the inferred spectral index at the source is consistent with theoretical predictions (see e.g. Biermann 1993).

NST12 proposed that the break below ~10 GeV arises either because of p–p interactions with ISM or scattering from magnetic inhomogeneities which may be dominated by clouds of a certain size (~1 au). However, from the p–p interaction argument, the time-scale is $\sim 3 \times 10^{7}$ yr, much larger than the typical residence time-scales of GCR inferred from other considerations.

In view of the arguments presented above, which make two reasonable assumptions that (a) the source spectrum of CRs is a power law in momentum and (b) the diffusion coefficient becomes energy independent and/or subdominant compared to convective transport, below ~5 GeV, we find that the NST12 spectrum can be explained without recourse to any additional processes, *although one cannot rule out other processes contributing towards the spectral shape*.

## 3 IONIZATION RATE

Next, we wish to constrain the NST12 spectrum by determining a low-energy cut-off below ~1 GeV after comparing with the observed molecular ionization rate.

Normalizing the spectrum derived by NST12 to the *PAMELA* flux above 200 GeV, and given the observed *PAMELA* flux at the energy bin centring 213.23 GeV to be $(4.17 \pm 0.08 \pm 0.2) \times 10^{-7}\,{\rm cm^{-2}\,sr^{-1}\,s^{-1}\,GeV^{-1}}$ (Adriani et al. 2011), we adopt the following spectrum for the diffuse GCR protons:

$$\begin{aligned}\frac{dN_{\rm p}}{dE_{\rm p}} &= 4.17\times10^{-7}\,{\rm cm^{-2}\,s^{-1}\,sr^{-1}\,GeV^{-1}} \\ &\quad\times\left(\frac{E_{\rm p}}{213.23\,{\rm GeV}}\right)^{\Gamma_2}, & E_{\rm p} \geq E_{\rm b} \\ &= 4.17\times10^{-7}\,{\rm cm^{-2}\,s^{-1}\,sr^{-1}\,GeV^{-1}} \\ &\quad\times\left(\frac{E_{\rm b}}{213.23\,{\rm GeV}}\right)^{\Gamma_2}\left(\frac{E_{\rm p}}{E_{\rm b}}\right)^{-\Gamma_1}, & E_{\rm p} < E_{\rm b} \\ &= 0\,, & E_{\rm p} \leq E_{\rm low}. \end{aligned} \qquad (1)$$

We follow Padovani et al. (2009) in our calculation of the ionization rate of molecular and atomic hydrogen. Only the direct ionization by primary protons is significant and dominates over other processes such as ionization by CR electrons and electron capture by CR protons by more than an order of magnitude. The ionization rate of $H_2$ by primary protons is

$$\zeta^{\rm H_2} = \int_{E_{\rm low}}^{\infty} \frac{dN_{\rm p}}{dE_{\rm p}}\,\sigma_{\rm p}^{\rm ion}(E_{\rm p})\,dE_{\rm p}\,, \qquad (2)$$

where $dN_{\rm p}/dE_{\rm p}$ is the CR proton spectrum at a given kinetic energy $E_{\rm p}$ and $E_{\rm low}$ is the low-energy limit of $E_{\rm p}$. The cross-section $\sigma_{\rm p}^{\rm ion}$ is given in Padovani et al. (2009). We also multiply this ionization rate by a factor of 5/3 in order to take into account the ionization by secondary electrons (Spitzer & Tomasko 1968).

The helium nuclei associated with the CR protons will enhance the ionization of the ISM molecules. In order to assess the enhancement factor introduced by the addition of helium nuclei, we use the ratio of protons to helium nuclei as a function of kinetic energy per nucleon as determined by *PAMELA* down to 0.4 GeV nucleon$^{-1}$, and use the proton spectrum of NST12 down to the same value of kinetic energy. We found that the ratio of proton to helium flux in *PAMELA* data (Adriani et al. 2011) can be fitted to an accuracy of ~10 per cent to the lowest kinetic energy (per nucleon) bin in their tables S3 and S4 by the following expression:

$$\frac{\Phi({\rm p})}{\Phi({\rm He})} \approx 4.47 + 12.68\,\tanh(\epsilon/2.247\,{\rm GeV})\,, \qquad (3)$$

where $\epsilon = E_{\rm kin}/A$ is the kinetic energy per nucleon. This ratio becomes constant above a value of $\epsilon \geq 20$ GeV nucleon$^{-1}$ and decreases at lower energies.

We find that the ionization rate increases by a factor of 1.48 if helium nuclei are included, using the ratio of p/He along with the NST12 spectrum, for a low-energy cut-off of 0.4 GeV nucleon$^{-1}$. We note that the p/He ratio as determined by *PAMELA* may, however, be affected by solar modulation, and therefore the enhancement of ionization may also be affected. If the low energy is shifted to 1 GeV nucleon$^{-1}$, then the ionization rate increases by a factor of 1.33, and for a cut-off at 10 GeV nucleon$^{-1}$, the corresponding factor is 1.23. We note that these factors are somewhat lower than the standard factor of 1.8 used in the literature (e.g. Rimmer et al. 2012). Keeping this uncertainty in mind, we multiply the ionization rate of protons by a factor of 1.5 below in order to take helium nuclei into account.

We show in Figs 2 and 3 the corresponding ionization rate $\zeta^{\rm H_2}$ as a function of the low-energy cut-off, $E_{\rm low}$, and also show the observed range of $\sim 0.6$–$2.4 \times 10^{-16}\,{\rm s^{-1}}$, for the rates in diffuse clouds with low molecular content (Gerin et al. 2010; Neufeld et al. 2010). We choose this range since the propagation effects are least likely to affect in the case of low-density diffuse clouds. The curves show the ionization rates for different combinations of $E_{\rm b}$ and $\Gamma_2$, but with $\Gamma_1 = 1.7$ in Fig. 2 and $\Gamma_1 = 1.9$ in Fig. 3. We note that NST12 derived a value of $\Gamma_1 = 1.7$ in the case of maximal bremsstrahlung component and provides an extreme limit.

The curves in Figs 2 and 3 show that the ionization rates are somewhat lower in the case of $\Gamma_1 = 1.7$ than for $\Gamma_1 = 1.9$. Also, we find that the corresponding values of $E_{\rm low}$ range between ~10 and 100 MeV, for the average $\xi^{\rm H_2} \sim 0.6$–$2.4 \times 10^{-16}\,{\rm s^{-1}}$ for diffuse clouds with low molecular content. We note that Schuppan et al. (2012), in their determination of the CR spectrum for MCs associated with SNRs, did not add the bremsstrahlung component, and therefore their predicted high-ionization rate is likely to be an overestimate.

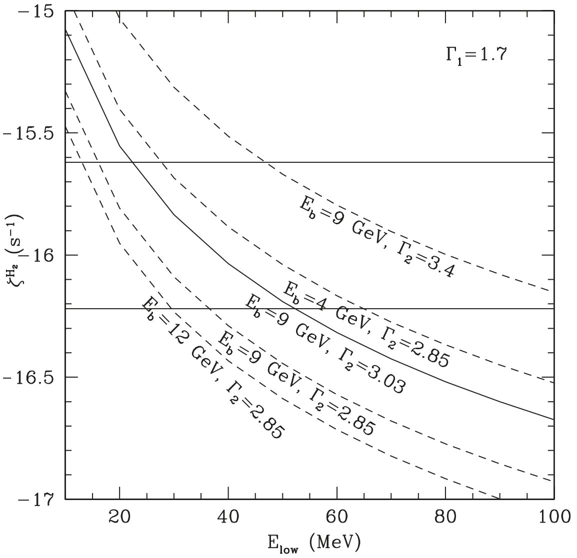

**Figure 2.** The molecular ionization rate $\zeta^{H_2}$ is calculated for the spectrum mentioned above, as a function of the low-energy cut-off $E_{\rm low}$, for a few combinations of the parameters $E_{\rm b}$ and $\Gamma_2$. The low-energy spectral index $\Gamma_1$ has been fixed at 1.7.

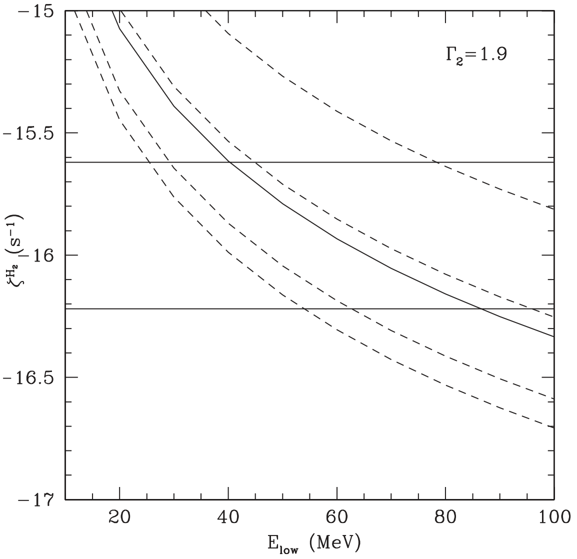

**Figure 3.** Same as Fig. 2 except for $\Gamma_2$ being fixed at 1.9.

## 4 DISCUSSION

The low-energy cut-off $E_{\rm low}$ can arise from a number of effects, and we would like to discuss these possibilities here.

### 4.1 Propagation effects

The low-energy cut-off $E_{\rm low}$ is related to the quantity of matter (grammage) the CRs traverse on average in the Galaxy and the ionization losses suffered by the protons below $E_{\rm p} \le E_{\rm low}$. The ionization loss for protons traversing the ISM is given by equation (4.22) of Mannheim & Schlickeiser (1994):

$$\frac{{\rm d}E_{\rm p}}{{\rm d}t}(\beta) = 4.96\times10^{-19}\,{\rm erg\,s^{-1}}(n_{\rm e}/{\rm cm^{-3}})\,\frac{\beta^2}{\beta^3+x_m^3}, \quad (4)$$

where $x_m = 0.0286(T/2\times10^6\,{\rm K})^{1/2}$, $T$ and $n_{\rm e}$ are the ambient (electron) temperature and density, and $\beta = v/c$. The ionization loss increases rapidly with decreasing proton energy.

For low-temperature ISM gas, this ionization loss of protons can also be expressed in terms of the grammage ($\sim nm_{\rm p}\beta ct$) as $\frac{\Delta E_{\rm p}}{E_{\rm p}} \sim \frac{6.7\times10^{-2}}{\beta^2(\gamma-1)}(\frac{\rm grammage}{10\,{\rm g\,cm^{-2}}})$, where $\gamma$ is the Lorentz factor. If we identify the cut-off energy $E_{\rm low}$ as due to ionization loss, then the inferred grammage for $E_{\rm low}$ = 10(50) MeV is ∼0.03(0.80) g cm$^{-2}$. The grammage for a 100-MeV proton is ∼3 g cm$^{-2}$.

The average grammage inferred for GeV CRs in our Galaxy is ∼10 g cm$^{-2}$ (e.g. Brunetti & Codino 2000). This grammage is believed to be smaller for lower energy protons, and goes down to ∼3 ± 1 g cm$^{-2}$, for $E_{\rm kin} \le$ 100 MeV, and also decreases with higher energies (e.g. see fig. 7 in Garcia-Munoz et al. 1987). Interestingly, this estimate of grammage inferred from the secondary/primary ratio is close to the grammage inferred from the interpretation of low-energy cut-off of 10–100 MeV from ionization rate, as discussed above. Our primary result is that using the NST12 spectrum allows us to identify the low-energy cut-off with ionization rate, in the sense that the grammage inferred from B/C ratio at this energy coincides with the grammage expected from ionization loss. That this near equality is difficult to achieve with other CR spectrum is evident. If we were to assume a CR spectrum without a flattening down to a low-energy cut-off, with a spectral index ∼2.85–3.0, then the Galactic average ionization rate would constrain the low-energy cut-off to ∼250–350 MeV. However, if this were to be identified as arising from ionization loss, then the corresponding grammage would be 15–30 g cm$^{-2}$, much larger than even the peak grammage at GeV scale. Therefore, our result shows that NST12 spectrum is consistent with the average Galactic ionization rate with a corresponding grammage of CR protons at low energy arising from ionization loss.

Previous works (Indriolo et al. 2009; Becker et al. 2011) have used a low-energy cut-off of ∼2 MeV for diffuse clouds and 10 MeV for dense clouds. It has been argued that the range of a 1-MeV proton is $8.5\times10^{-4}$ g cm$^{-2}$, corresponding to a column density of $\sim5\times10^{20}$ H cm$^{-2}$. Indriolo et al. (2009) considered a low-energy cut-off of 2 MeV for diffuse clouds with density $\le10^3$ cm$^{-3}$, and Becker et al. (2011) assumed a low-energy cut-off of 10 MeV for MCs near SNRs, with density $\ge10^3$ cm$^{-3}$. Here also, the idea has been to find a consistency between the CR spectrum, the low-energy cut-off and the ionization rate. However, the calculations mentioned here have either assumed a CR spectrum (and found the ionization rate) or found a CR spectrum for a given ionization rate. At times, finding a convergence has been difficult. For example, Indriolo et al. (2009) found that their model CR spectrum that took propagation of CRs in the Milky Way produced a lower ionization rate than observed, and they suggested the presence of an additional component of low-energy CRs. Our result here shows that with the NST12 spectrum, a convergence of low-energy cut-off, grammage and ionization rate is possible.

Also, our results show that even for diffuse clouds a low-energy cut-off below 10 MeV is inconsistent with the Galactic average ionization rate and that the low-energy cut-off lies in the range 10–100 MeV. Therefore, the cut-off in dense MCs is likely to be larger than this value, and our results suggest that the ionization rate in MCs with SNRs, as in Becker et al. (2011), is likely to be an overestimate because of the assumption of a low value of cut-off.

Interestingly, in the model of Biermann et al. (2001), the CR protons from SNR shocks in ISM are expected to have a grammage of ∼1 g cm$^{-2}$, similar to the convergence value found in our analysis. CRs from massive star supernovae are believed to consist of mainly heavy nuclei and their spallation products, while supernovae of moderate-mass stars produce predominantly CR protons. The secondary CRs produced in the spallation interactions of massive star supernovae with stellar wind material are expected to have a much larger grammage. Therefore, our results support the acceleration of CR protons in SNR shocks in ISM.

### 4.2 Magnetic field effects

Cesarsky & Völk (1978) proposed that CR streaming instability in the presence of magnetic field in MCs would excite Alfvén waves which would scatter off low-energy CRs (Skilling & Strong 1976). They estimated that this would screen the MCs from Galactic low-energy CRs and that the low-energy cut-off would be related to the cloud size *R*, particle density *n* and magnetic field *B* as

$$E \sim 50\,\mathrm{MeV}\,(R/8.2\,\mathrm{pc})^{0.5}\,(n/2\times10^{3}\,\mathrm{cm}^{-3})^{0.5}\,(B/50\,\mu\mathrm{G})^{-0.5}\,. \tag{5}$$

This shows that for a typical MC magnetic field of a few μG (Curran & Chrysostomou 2007), the low-energy cut-off can be as large as $\geq$100 MeV. However, if we turn the argument around, then the typical values of $E_{\rm low}$ derived above for CRs inside MCs imply that the ability of magnetic fields to screen low-energy CRs in MCs is smaller than previously thought, since it is clear that in order to sustain the typical average ionization rate in MCs, $E_{\rm low} \leq 100$ MeV.

## 5 SUMMARY

In summary, we have studied the GCR proton spectrum recently inferred from gamma-ray emission from MCs near the Gould belt. We have identified the inferred break of the energy spectrum at a few GeV as a consequence of (a) the source CR spectrum being a power law in momentum, $p^{-2.45}$, and (b) the diffusion coefficient for protons being independent of energy below a few GeV. We have shown that this renders the CR spectrum consistent with that observed at high energies. We have also derived a low-energy cut-off for the CR spectrum, after a comparison with the observed Galactic ionization rate of molecular hydrogen (since the ionization is dominated by protons), and found its values to lie in the range 10–100 MeV. We have then shown that the NST12 spectrum is consistent with three independent phenomena: (a) ionization loss that corresponds to a particular value of grammage, (b) grammage as inferred from other means and (c) the average Galactic ionization rate.

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