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Can a cosmic ray carrot explain the ionization level in diffuse molecular clouds?

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ABSTRACT

Low-energy cosmic rays are the major ionization agents of molecular clouds. However, it has been shown that, if the cosmic ray spectrum measured by Voyager 1 is representative of the whole Galaxy, the predicted ionization rate in diffuse clouds fails to reproduce data by 1–2 orders of magnitude, implying that an additional source of ionization must exist. One of the solutions proposed to explain this discrepancy is based on the existence of an unknown low-energy (in the range 1 keV–1 MeV, not probed by Voyager) cosmic ray component, called *carrot* when first hypothesized by Reeves and collaborators in the seventies. Here we investigate the energetic required by such scenario. We show that the power needed to maintain such low-energy component is comparable of even larger than that needed to explain the entire observed cosmic ray spectrum. Moreover, if the interstellar turbulent magnetic field has to sustain a *carrot*, through second-order Fermi acceleration, the required turbulence level would be definitely too large compared to the one expected at the scale resonant with such low-energy particles. Our study basically rules out all the plausible sources of a cosmic ray *carrot*, thus making such hidden component unlikely to be an appealing and viable source of ionization in molecular clouds.

Key words: ISM: clouds – cosmic rays – ISM: magnetic fields.

1 INTRODUCTION

The ionization level of molecular clouds (MCs) is a crucial ingredient that determines their chemistry and the coupling between the gas and the magnetic field (see e.g. Dalgarno 2006 for a review). The ionization rate of MCs is observed to decrease with increasing cloud column density, with values that can reach $\approx 10^{-15}\,\mathrm{s}^{-1}$ in diffuse clouds, down to $\approx 10^{-17}\,\mathrm{s}^{-1}$ in denser clouds (see Padovani & Galli 2013 and references therein).

Cosmic rays (CRs), especially the low energy ones (below $\approx$ 1 GeV), are widely recognized (see e.g. Padovani, Galli & Glassgold 2009) as the major, or most likely the only, candidate able to ionize the interior of MCs, being the other main sources of ionization, namely UV photons and X-rays, unable to penetrate deeply inside MCs (Krolik & Kallman 1983; Silk & Norman 1983; McKee 1989).

Locally, the interstellar low-energy CR spectrum has been measured down to few MeV by Voyager 1, which is now thought to be far enough from the Sun, as to be unaffected by the solar modulation (Krimigis et al. 2013; Stone et al. 2013; Cummings et al. 2016).

Several theoretical estimates of the CR induced ionization in MCs have been presented in the literature, starting from the pioneering works of Hayakawa, Nishimura & Takayanagi (1961) and Tomasko & Spitzer (1968), based on a simple extrapolation to low energies of the observed CR spectrum, to more refined models which take into account the propagation and energy losses of CRs in clouds (Skilling & Strong 1976; Cesarsky & Volk 1978; Morfill 1982; Padovani et al. 2009; Morlino & Gabici 2015; Schlickeiser, Caglar & Lazarian 2016; Ivlev et al. 2018; Phan, Morlino & Gabici 2018). In particular, Phan et al. (2018) showed that if one assumes that the average low-energy proton and electron spectrum in the Galaxy is the same as measured by Voyager 1, the inferred ionization rate inside diffuse MCs is ∼1–2 orders of magnitude smaller than the observed one. As pointed out by Phan et al. (2018), improvements of these models that, for instance, include also a description of dense and clumpy media and a more realistic modelling of the transition between different phases of the interstellar medium (ISM), are unlikely to enhance the predicted ionization rate by such large factor (see also Morlino & Gabici 2015).

Thus, in order to reconcile predicted and measured ionization rates, one should either invoke a new source of ionization inside MCs, or question the validity of assuming the Voyager 1 spectrum

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to be representative of the whole CR spectrum in Galaxy. Several possibilities have been put forward: (i) the possible presence of MeV CR accelerators inside MCs (see e.g. Padovani et al. 2015, 2016); (ii) inhomogeneities in the distribution of low-energy CRs in the Galaxy (see e.g. Cesarsky 1975; Gabici & Montmerle 2015; Nobukawa et al. 2015, 2018); (iii) the existence of a still unknown CR component emerging at energies below few MeV (the smallest energy detected by Voyager 1). Such component, called *carrot*, was first proposed by Meneguzzi, Audouze & Reeves (1971) to explain the abundances of light elements, and has recently been reconsidered by Cummings et al. (2016, who called it *suprathermal tail*).

In this paper we focus on the *carrot* scenario and we analyse in detail the implications of the possible presence of a CR population at energies below few MeV. [1] In particular, we estimate the power that has to be injected in low-energy CRs in order to keep in the whole Galactic disc a population able to account for the observed ionization rate in MCs. We do so by assuming that the *carrot* component is uniformly distributed both inside clouds and in the rest of the ISM. The power estimated in that way represents a very conservative lower limit, since in a more realistic scenario low-energy CRs present in the ISM penetrate the cloud and their transport and energy losses in MCs have to be taken into account. As shown by Phan et al. (2018), the ionization rate predicted in this case would be smaller than in the simple scenario presented here. Here we show that, due to the relatively short ($\lesssim 10^5$ yr, see equation 5) lifetime of sub MeV CRs in the ISM, in order to maintain a very low energy and hidden CR component able to explain the observed ionization rates, it would be necessary for the potential sources to inject in the ISM a power comparable to or larger than that needed to explain the whole observed CR spectrum. This result poses a serious concern on the viability of a *carrot* scenario.

We also explore the implications of assuming that such component be accelerated by the turbulent magnetic field in the ISM, through second-order Fermi acceleration (see e.g. Osborne & Ptuskin 1988; Jokipii 2001; Thornbury & Drury 2014; Drury & Strong 2017). However, we show that in this case the level of turbulence required at the scale resonant with CRs at the relevant energies is much larger than the one usually accepted. This brings additional support to the idea that a CR *carrot* at energies below the smallest one detected by Voyager 1 fails to provide a solution to the problem of the ionization rate in MCs.

2 POWER REQUIREMENT

Let us assume the presence of a CR (electron and/or proton) component at a given energy $\tilde{\rm E} \lesssim 3\,{\rm MeV}$ (energies smaller than those detected by Voyager 1), uniformly distributed in the whole Galactic disc, including the interior of MCs. For simplicity, we assume that the distribution function of such component is

$$f(E) = A\delta(E - \tilde{E}), \tag{1}$$

where A is a normalization constant that has to be determined.

We do so by imposing that the H_2 ionization rate produced by CRs (electrons or protons) with the distribution function given by equation (1), equals the average value, $\xi \approx 4 \times 10^{-16}\,{\rm s}^{-1}$, detected in diffuse clouds (see e.g. Indriolo, Fields & McCall 2009).

Such ionization rate can be computed, following the approach by Padovani et al. (2009) and Phan et al. (2018), as

$$\xi^{\rm p} = \int_I^{E_{\rm Max}} f_{\rm p}(E) v_{\rm p} \left[\left(1+\phi_{\rm p}(E)\right)\sigma^{\rm p}_{\rm ion}(E) + \sigma_{\rm ec}(E)\right] {\rm d}E\,, \tag{2}$$

$$\xi^{\rm e} = \int_I^{E_{\rm Max}} f_{\rm e}(E) v_{\rm e} \left[1+\phi_{\rm e}(E)\right]\sigma^{\rm e}_{\rm ion}(E)\, {\rm d}E. \tag{3}$$

Here $f_{\rm p(e)}(E)$ is the CR proton(electron) distribution function, $v_{\rm p(e)}$ is the incident CR velocity, $\sigma^{\rm p(e)}_{\rm ion}$ is ionization cross-section and $\sigma_{\rm ec}$ is the electron capture cross-section, $\phi_{\rm p(e)}$ are the average secondary ionizations per primary ionization (Krause, Morlino & Gabici 2015), $I = 15.603$ eV is the H_2 ionization potential.

Once determined the overall normalization of the *carrot* distribution function, the power needed in order to sustain such component in the whole Galactic disc can be estimated as

$$P(\tilde{E}) = \frac{A(\tilde{E})\tilde{E}V_{\rm disc}}{\tau_{\rm loss}(\tilde{E})}. \tag{4}$$

Here $V_{\rm disc}$ is the disc volume (radius $\rm R_d \sim 15\,kpc$, height $\rm h_d \sim 300\,pc$) and

$$\begin{aligned} &\tau_{\rm loss,p}(E) \approx 6\, E_{\rm keV}^{4/3}\,{\rm yr} && \text{for E in 1 keV–1 MeV} \\ &\tau_{\rm loss,e}(E) \approx 3 \times 10^2 E_{\rm keV}\,{\rm yr} && \text{for E in 1 keV–1 MeV} \end{aligned} \tag{5}$$

are the approximate expressions for the CR proton and electron energy loss time in the Galactic disc. Such energy losses are mainly due to ionization losses in the neutral phases of the ISM and Coulomb losses in the ionized phases of the ISM (see e.g. Schlickeiser et al. 2016).

The expressions of equation (5) are computed as

$$\tau_{\rm loss(p,e)}(E) = \frac{1}{\sum_i r_{i({\rm p,e})} f_i}, \tag{6}$$

where r_i and f_i are the loss rate and filling factor, respectively, for the different phases of the ISM. The ISM is approximated as mainly constituted by three phases (see e.g. Osterbrock & Bochkarev 1989): (1) warm neutral medium (WNM), mostly made of neutral atomic hydrogen (density $\approx 0.5\,{\rm cm}^{-3}$, volume filling factor ≈25 per cent, temperature ≈8000 K); (2) warm ionized medium (WIM), mostly made of ionized atomic hydrogen (density $\approx 0.5\,{\rm cm}^{-3}$, volume filling factor ≈25 per cent, temperature ≈8000 K); (3) hot ionized medium (HIM), mostly made of ionized atomic hydrogen (density $\approx 0.006\,{\rm cm}^{-3}$, volume filling factor ≈50 per cent, temperature $\approx 10^6$ K).

In Fig. 1 we show the power estimated in equation (4) for CR electron and proton energies in the range 1 KeV–1 MeV. We compare it with the total power (see e.g. Strong et al. 2010) injected by sources in the observed CR spectrum ($\approx 10^{41}\,{\rm erg\,s}^{-1}$) and electron spectrum ($\approx 10^{39}\,{\rm erg\,s}^{-1}$). We also show an estimate of the total power in CR protons needed to keep in the whole Galactic disc the suprathermal tail invoked in Cummings et al. (2016) as

$$P_{\rm C-2016} = \int_{1\,{\rm KeV}}^{1\,{\rm MeV}} \frac{4\pi J(E) E}{v_{\rm p}(E)} \frac{V_{\rm disc}}{\tau_{\rm loss,p}(E)} {\rm d}E \approx 2 \times 10^{42}\,{\rm erg\,s}^{-1}, \tag{7}$$

where $J(E)$ is the CR proton flux of the suprathermal tail (see fig. 16 of Cummings et al. 2016).

Remarkably, the plot in Fig. 1 illustrates that, due to the short lifetime of low-energy CRs in the ISM (see equation 5), a CR *carrot*

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[1] We do not consider here the effect of the CR carrot on the production of light elements. For a recent review of this topic see Tatischeff & Gabici 2018.

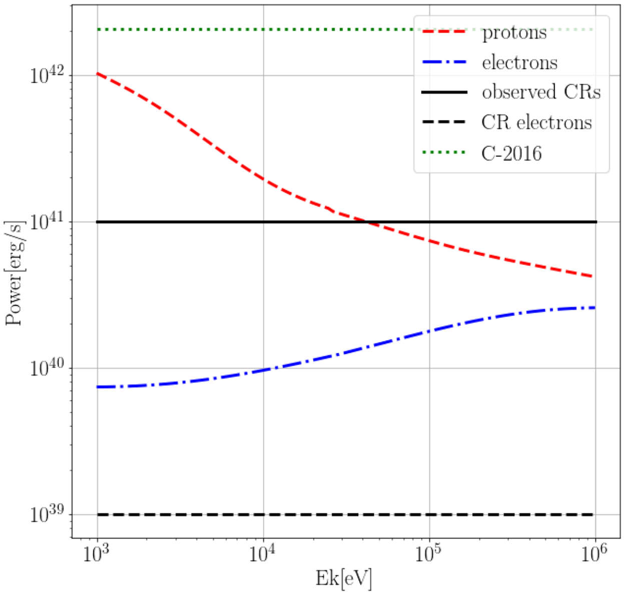

Figure 1. Power needed in CR protons and electrons in order to keep a *carrot* at a given energy in the whole Galactic disc, able to predict (without taking into account the CR penetration in MCs) an ionization rate of $4 \times 10^{-16}\,\mathrm{s}^{-1}$, as compared with the power needed to sustain the observed CR Galactic population (black, solid line) and the observed CR electron spectrum (black, dashed line), respectively. The line marked as C-2016 is the power required in CR protons in order to keep the suprathermal tail invoked in Cummings et al. (2016) in the whole Galactic disc .

(or the suprathermal tail of Cummings et al. 2016) would require a power injection comparable or even larger than that already needed in order to account for the whole observed CR spectrum ($\approx 10^{41}$ erg s^{-1}). The situation is especially dramatic for electrons, given that the observed CR power for them is $\approx 10^{39}$ erg s^{-1}.

Note that 10^{41} erg s^{-1} roughly corresponds to 10 per cent of the total power of Galactic supernova explosions. Since supernova remnants are considered the major source of Galactic CRs (see e.g. Blasi 2013), our result implies that the existence of a CR *carrot* would require either an unreasonably large (in some cases even larger than 100 per cent) CR acceleration efficiency for known CR sources, either the existence of another, much more powerful (and thus implausible), class of sources.

Notice that this result is not expected to change with different assumptions on the spectral shape of the low-energy component. In fact, the required power injection is minimum for a proton (electron) *carrot* at 1 MeV(1 keV), as shown in Fig. 1. Any choice of a broader spectrum in the range 1keV–1MeV, able to predict the same ionization level in MCs, will inevitably imply a larger power injection.

Moreover, this estimated power is a very conservative lower limit. In fact here we assumed that the unknown CR component is uniformly distributed in the whole Galactic disc and inside clouds. However, CRs have to penetrate the cloud. As illustrated by Phan et al. (2018), taking into account this effect leads to a lower predicted level of ionization. This can be easily seen if, for instance, we consider the average distance travelled by CR electrons and protons inside a cloud before losing all their energy due to ionization losses that we estimate as

$$L_{\mathrm{loss}}(E) = v(E)\tau_{\mathrm{loss}}(E, n_{\mathrm{c}}), \qquad (8)$$

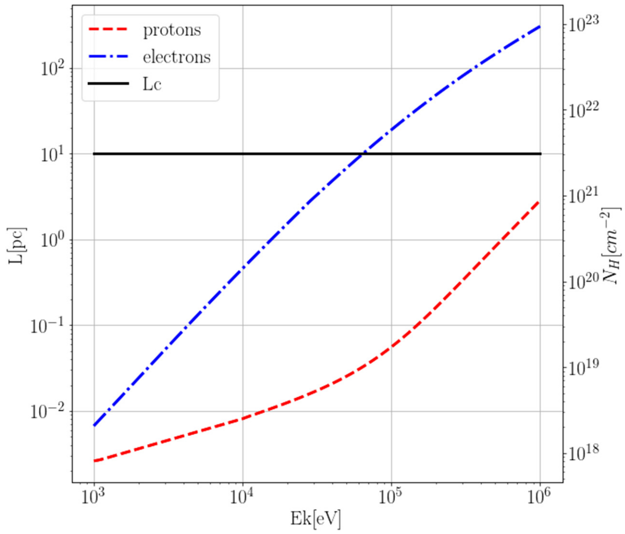

Figure 2. Average distance travelled by CR electrons (blue, dot–dashed line) and protons (red, dashed line) within a cloud ($\mathrm{n_c} = 100\,\mathrm{cm}^{-3}$) in a loss time. The typical cloud size is assumed to be $L_{\mathrm{c}} = 10$ pc (black, solid line).

where

$$\tau_{\mathrm{loss,p}}(E, n_{\mathrm{c}}) \approx \begin{cases} \frac{500}{n_{\mathrm{c}}}\,\mathrm{yr} & \text{for E in 1 keV–0.1 MeV} \\ 1.1 \times 10^4 \frac{E_{\mathrm{MeV}}^{4/3}}{n_{\mathrm{c}}}\,\mathrm{yr} & \text{for E in 0.1–1 MeV} \end{cases}$$

$$\tau_{\mathrm{loss,e}}(E, n_{\mathrm{c}}) \approx 10^5 \frac{E_{\mathrm{MeV}}}{n_{\mathrm{c}}}\,\mathrm{yr} \qquad \text{for E in 1 keV–1 MeV} \qquad (9)$$

are approximate expressions for the CR ionization loss time (Padovani et al. 2009; Phan et al. 2018) for CR electrons and protons in a cloud of H_2 density given by n_{c}.

In Fig. 2 we compare this typical distance for CR electrons and protons of energy in the range 1 KeV–1 MeV inside a cloud of $n_{\mathrm{c}} = 100\,\mathrm{cm}^{-3}$, with a typical cloud size $L_{\mathrm{c}} = 10$ pc. The result is that protons of these energies and electrons of $E \lesssim 0.1$ MeV would not even be able to cross a typical cloud.

Notice that also keeping a CR *carrot* inside clouds instead that in the whole Galactic disc would lead an unsustainable power requirement. In this case, the rate at which CRs should be provided to the cloud can be derived by using equations (4) and (9), provided that V_{disc} is substituted with V_{cloud}. The CR power obtained in this way is compared in Fig. 3 to a characteristic maximal cloud power P_{c} obtained by dividing the cloud gravitational energy $E_{\mathrm{g}} = \frac{3}{5}\frac{GM_{\mathrm{c}}^2}{R_{\mathrm{c}}}$ by its typical lifetime τ_{life}. We adopt typical cloud parameters $\mathrm{R_c} = 10\,\mathrm{pc}$, $\mathrm{n_c} = 100\,\mathrm{cm}^{-3}$ and $\tau_{\mathrm{life}} \sim 10^7$ yr (see e.g. Heyer & Dame 2015). The CR power largely exceeds P_{c}, making the *carrot* scenario non-viable.

3 ACCELERATION IN THE TURBULENT MAGNETIC FIELD

The results of Section 2 already poses serious doubts on the *carrot* scenario for the explanation of the observed ionization rate in MCs.

In order to bring additional support to this result, we also explore a possible major source of low-energy CRs, namely the second-order Fermi acceleration in the turbulent interstellar magnetic field (see e.g. Osborne & Ptuskin 1988; Jokipii 2001; Thornbury & Drury 2014; Drury & Strong 2017). The acceleration time-scale due to this

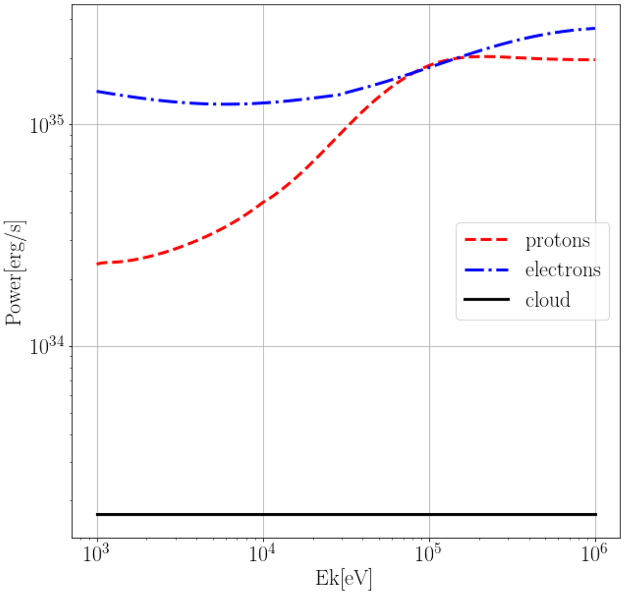

Figure 3. Power in CR electrons and protons in order to keep a *carrot* at a given energy within a cloud ($n_c = 100\,\mathrm{cm}^{-3}$, radius $R_c \sim 10$ pc), able to predict an ionization rate of $4 \times 10^{-16}\,\mathrm{s}^{-1}$. This is compared with the maximum power that a cloud can provide (black, solid line), given by $P_c = E_{\rm grav}/\tau_{\rm life}$ ($\tau_{\rm life} \sim 10^7$ yr, $E_{\rm grav} = \frac{3}{5}\frac{GM_c^2}{R_c}$).

process is given by (see equation 20 of Thornbury & Drury 2014)

$$\tau_{\rm acc}(E) = \frac{9}{4}\frac{D(E)}{v_{\rm A}^2}, \tag{10}$$

where $D(E) = \frac{1}{3}\frac{v(E) r_{\rm L}(E)}{I(k_{\rm res})}$ is the spatial diffusion coefficient for particles of energy E and $v_{\rm A} = B_0/\sqrt{4\pi\rho}$ is the Alfv´en speed. Here v and $r_{\rm L}$ are the particle velocity and Larmor radius, $I(k_{\rm res}) = W(k_{\rm res})k_{\rm res}$ is the level of turbulence, $(\delta B/B_0)^2$, at the resonant scale $k_{\rm res}(E) = 1/r_{\rm L}(E)$, B_0 is the background magnetic field, and ρ the average mass density of the background medium.

Since low-energy CRs lose energy in the ISM on a time-scale given by equation (5), in order to keep a CR carrot at energy E the level of magnetic turbulence at the resonant scale $k_{\rm res} = 1/r_L(E)$ have to be such that

$$\tau_{\rm loss}(E) = \tau_{\rm acc}(E), \tag{11}$$

namely

$$I(k_{\rm res}) = \frac{9}{4}\frac{v\, r_{\rm L}}{3v_{\rm A}^2}\frac{1}{\tau_{\rm loss}}. \tag{12}$$

A plot of the needed level of turbulence is shown in Fig. 4 for $B_0 = 3\,\mu$G, in the case of CR electrons and protons of energy in the range 1 KeV–1 MeV.

Remarkably, the inferred $I(k_{\rm res})$ at the energies relevant for this paper are larger than, for instance, that expected at the scale resonant with ~1 GeV in order to account for accepted (see e.g. Trotta et al. 2011) values of the spatial diffusion coefficient (D(1 GeV) $\sim 10^{28}\,\mathrm{cm}^2\,\mathrm{s}^{-1}$, I(1 GeV) $\sim 9 \times 10^{-7}$). This is quite unlikely to happen, since in any physical model of interstellar magnetic turbulence $I(k)$ is a decreasing function of k (see e.g. Sridhar & Goldreich 1994; Goldreich & Sridhar 1995). The present result, together with the results of Section 2, makes very difficult for a CR *carrot* (or suprathermal tail) to represent a feasible model able to reconcile the predicted and observed ionization rates in MCs.

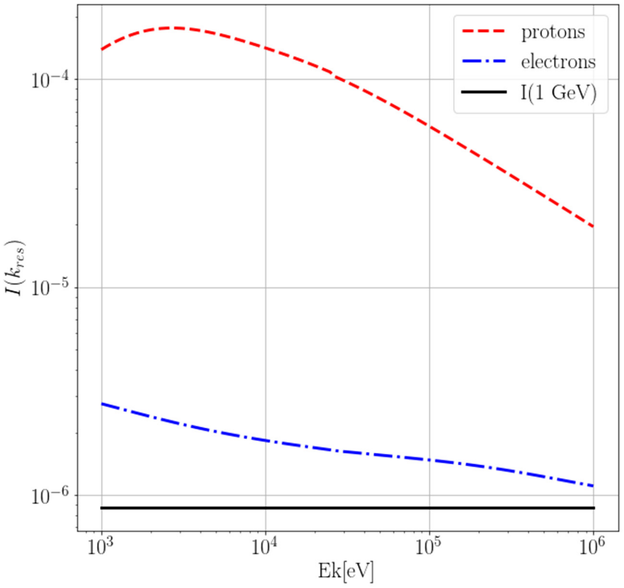

Figure 4. Level of magnetic turbulence needed to steadily maintain, through second-order Fermi acceleration, sub MeV CR electrons and protons in the ISM ($B_0 = 3\,\mu$G). We show for comparison the turbulence expected at the scale resonant with ~1 GeV in order to account for accepted values of the spatial diffusion coefficient (D(1 GeV) $\sim 10^{28}\,\mathrm{cm}^2\,\mathrm{s}^{-1}$) at that energy.

4 CONCLUSIONS

Phan et al. (2018) showed that, if the CR electron and proton spectra measured by Voyager 1 are representative of the whole Galaxy, the penetration of such CRs inside diffuse MCs cannot account for the observed level of ionization in such clouds by 1–2 orders of magnitude. This is an intriguing result that currently lacks an explanation. Among the solution proposed to this puzzle, there is the possibility that the CR electron and proton spectra may contain a still unknown component, called *carrot*, at energies lower than the one detected by Voyager 1.

In this paper we investigated this possibility, focusing in particular on the energetics involved if such a *carrot* has to account for the average ionization rate detected in diffuse MCs.

We found that, due to the energy losses suffered by low-energy CRs in the ISM, the power needed to be injected by the potential sources in such component is comparable or larger than that needed to explain the observed CR spectrum, even without taking into account the actual penetration of these low-energy CRs inside clouds, which would make this energy requirement even more severe.

Moreover, if we consider the interstellar turbulent magnetic field as a possible source of this *carrot*, through second-order Fermi acceleration, the required turbulence level would be definitely too large compared to the one expected at the scale resonant with such low-energy particles.

Our study basically rules out, on an energy basis, any possible source of a CR *carrot*, thus making such hidden component unlikely to be an appealing and viable source of ionization in MCs.

This conclusion encourages further studies of the possible solutions to the discrepancy between predicted and observed ionization rates in MCs. Among them, some promising ones remain the one already mentioned in the introduction and in Phan et al. (2018): (i) the possible presence of sub GeV CR accelerators inside MCs; (ii) prominent inhomogeneities in the distribution of low-energy CRs in the Galaxy. With this respect, we note that, given our peculiar location inside an ISM cavity (the local bubble, see e.g. Cox 1998), the CR spectrum measured by Voyager 1 might simply reflect local properties, rather than representing the typical spectrum of CRs in the Galaxy.

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