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The local cosmic-ray spectrum probed by gamma-ray observations

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We propose a new sampling of the local ($\lesssim$2 kpc) cosmic-ray (CR) spectrum based on Fermi-LAT analysis of molecular clouds (MCs), for which we have a new improved distance estimation based on GAIA observations. The spatial and spectral distribution of CRs can effectively be proven by observing the gamma rays that they produce while interacting with the interstellar medium (ISM). In particular, the interactions of CR nuclei with the interstellar gas produce a gamma-ray flux which depends only on the CR spectrum at the location of the interaction and on the density of the target. Molecular clouds are small regions (10-100 pc) characterized by an enhanced gas density (n$\sim$100-1000 cm^{-3}) and hence they serve as perfect targets to localize and constrain CRs. The advent of GAIA revolutionized the understanding of the geometry of the local medium, providing a very precise three-dimensional mapping of the local dust. We extract the spectral energy distribution between a few hundred MeV to a few hundred GeV of a sample of clouds localized by GAIA in the local medium between 100 pc to 2 kpc. Investigating the local CR distribution is a fundamental step to understand if local propagation and/or acceleration effects are playing a role in shaping the observed CR spectrum that we measure at Earth.

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1. Introduction

The cosmic-ray (CR) spectrum at least up to the so-called knee ($\sim 10^{15}$ eV) is believed to be the result of acceleration and propagation of particles in the Galaxy [1]. Precise measurements over the last decades, unveiled several features in the spectral distribution of CRs, which hardens above 300 GV and softens again around a few TV. Alongside, Voyager recently measured for the first time the CR spectrum outside the heliosphere, thus unaffected by solar modulation [2]. In order to understand whether this spectrum is characteristic of other parts of the Galaxy, one can compare it with the CR spectrum derived by gamma-ray observations. CRs interacting with the interstellar medium (ISM) indeed produce gamma radiation, that can be measured to infer the CR spectral distribution at the location of the interaction. Analysis of Fermi-LAT data both targeting the large-scale diffuse emission [3–5] and molecular clouds [6, 7] unveiled a certain heterogeneity in the gamma-ray emissivity, especially towards the inner Galaxy, where the gamma-ray emissivity is enhanced of a factor of a few, compared to the locally measured one, probably due to a higher density of sources in the vicinity of the targeted gas, or along the line of sight [6, 8]. The emissivity measured in the local ~ 8 kpc galactocentric ring (hereafter *local emissivity*) is expected to be similar to the emissivity derived from direct measurements of CRs (hereafter *direct emissivity*), as confirmed as well by measurements of local molecular clouds [6, 9, 10], even though exception are found even in very close clouds [11]. However, when accounting for Voyager data, the direct emissivity is a factor ~ 2 lower than the local emissivity [12]. This shift could be due to an excess emissivity in the local ring, similarly to what happens in the inner Galaxy, but in a smaller amount, or it could be due to very local properties of the CRs. Notice that Tatischeff and collaborators pointed out that a low-energy break in the CR injection spectrum is needed to explain Voyager data [13, 14]. In order to investigate these two scenarios, we conducted a new gamma-ray analysis on a sample of molecular clouds, located in the local ring. We extract their emissivity and compare it with the local and the direct emissivity.

2. Molecular clouds traced by Gaia

We use the catalog of Zucker and collaborators [15] to select the clouds for our analysis. They report updated distances measured over 326 line of sights (LoS) for nearby molecular clouds with distances spanning from 75 pc to 2500 pc. They constrain the distance of the clouds by measuring the extinction of background stars with known distance. This results in clouds distances measured with accuracy of $\approx 10\%$.

To compose our sample, as a selection criterion, we imposed that no source from the Fermi 4FGL-DR3 catalog [16] was found within a radius of 0.5 deg from the clouds. Moreover we excluded from the analysis any clouds that overlapped with another cloud of the sample, if their relative distance was larger than 100 pc. We include instead in the sample clouds that overlap, if they are located within 100 pc from each other. In the latter case we consider an area centered at the average longitude and latitude of the group of overlapping clouds. For each region we derive the column density of the gas that serves as target for the CRs from dust opacity maps measured at 353 Hz by the Planck satellite [17]. We use the dust-to-gas conversion factor, $X_{dust} = (\tau_D/N_H)^{-1} = 8.3 \times 10^{25}$ cm^{-2}[17]. The latter trace linearly the hydrogen density, at least up to $\sim 10^{22}$ cm^{-2}, where the

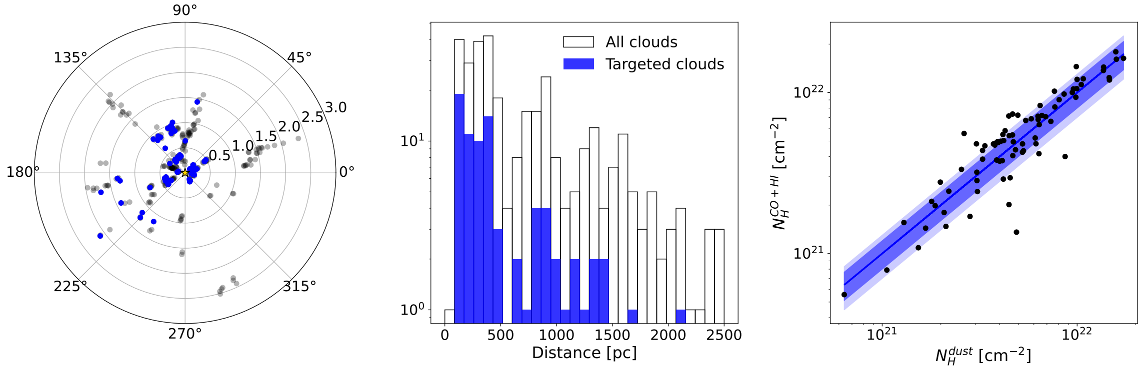

Figure 1: Left panel: space distribution on the (l, d)-plane of the clouds of the considered catalog[15], the blue points represent the analyzed clouds. The yellow star shows the position of the Sun. Central panel: distribution of clouds distances from us. Right panel: the column density of the clouds calculated with two different tracers, as described in the text. The inner and outer bar represent a 20% and a 30% uncertainty, respectively.

dust-to-gas ratio starts to increase, probably due to increased dust emissivity [18]. We calculate the column density both from Planck and from CO ($X_{CO} = 2 \times 10^{20}$ cm^{-2} K^{-1} km^{-1} s) [19] and HI maps ($X_{HI} = 1.8 \times 10^{18}$ cm^{-2} K^{-1} km^{-1} s [20]), and see that they are comparable within ~30%. The densities of the targeted regions spans from 5×10^{20} cm^{-2} to 2×10^{22} cm^{-2} (see figure 1), so we consider the linear relation a good approximation, being far from the range of HI self absorption ($N_H < 10^{20}$ cm^{-2}) and of dust-to-gas non linearity ($N_H > 10^{22}$ cm^{-2}). We consider as a systematic uncertainty the difference between the column density calculate with the two tracers. Moreover, we checked that at the location of the chosen clouds the gas is all concentrated in a single location, by checking the velocity distribution of the CO and HI in the considered regions.

3. Observations

We analyze Fermi-LAT Pass8 data collected over more than 14 years using the `fermipy` software package. We considered the energy range 100 MeV – 870 GeV and imposed standard analysis cuts on the data quality (`evclass`:128, `evtype`: 3, `zmax`:90, `DATA_QUAL>0 && LAT_CONFIG==1`). We include in the starting model all the sources of the 4FGL-DR3 catalog [16], as well as the template for the extra-galactic diffuse emission provided by the Fermi collaboration. To model the Galactic emission we used a customized template, constructed from the map of dust as described in details in [6, 7]. The cloud spatial template is a cut-out from the dust map. The cut is performed on a 1°x1° region centered at the LoS centers reported by [15]. As a spectral model for the clouds and the surrounding gas, we use a broken power-law. After performing a global fit of the region of interest, we derive the spectral energy distribution (SED) for the clouds. In figure 2 we plot the integral emissivity derived from the clouds. We integrate the SED above 3 GeV and derive the emissivity by dividing it by the total number of hydrogen atoms in the clouds. We use the dust-derived column density, but we account for the differences with other tracers in the systematic errors. We detect 74 out of 80 targeted clouds. We plot as a upper limits the clouds for which we don't have a detection. The emissivity derived in this work from clouds are compared with the

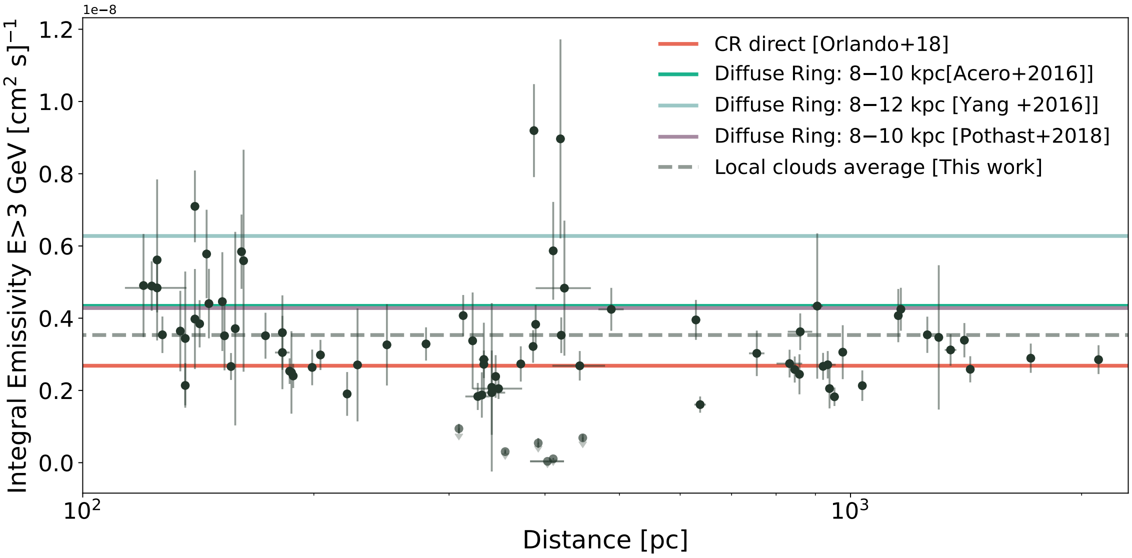

Figure 2: Radial distribution (from the Sun) of the integral emissivity derived for the analyzed clouds above 3 GeV. The systematic error on the flux is evaluated from the column density estimations. The horizontal solid lines indicate the values derived from the direct emissivity and from the local emissivity, as reported by different works. The dashed line instead represents the average evaluated from the clouds detected in this work.

emissivity calculated from observations of the local diffuse medium in different analyses [3–5] and from the direct measurements [12], plotted as horizontal bars in figure 2. In the plot we add also the average value for the emissivity derived from the detected clouds.

4. Discussion and conclusion

The results presented here on the gamma-ray integral emissivity are a proxy of the CR distribution. In figure 3 the color-map shows the relative difference between the derived emissivity and the direct emissivity [12]. From figure 2 and figure 3 it emerges that in many regions the emissivity matches with the direct emissivity suggesting that this is not characteristic only of the solar neighborhood. On the other hand, a large scatter over almost one order of magnitude is detected in the derived emissivities. The average value, calculated excluding the upper-limit cases, falls between the local and the direct emissivity. We notice a few enhancements localized in some regions. For example the region of the Orion Lam molecular clouds located at 500 pc from us, is enhanced of a factor ~ 3 compared to the direct emissivity. The nature of this enhancement needs to be investigated. Alongside, we notice a few locations with a detected emissivity which is lower than the direct emissivity. It should be clarified if this effect is not due to an overestimation of the mass, otherwise it could indicate an effective deficiency of CRs inside these clouds. This is similar to what emerged in recent analysis of the Taurus and Perseus molecular clouds [21], but concerns much higher energies, where is even more difficult to avoid CR penetration, with average parameters of the diffusion coefficient [22]. We notice that the regions with the highest differences (both in excess and deficiency) from the direct emissivity have a similar (within uncertainty) column

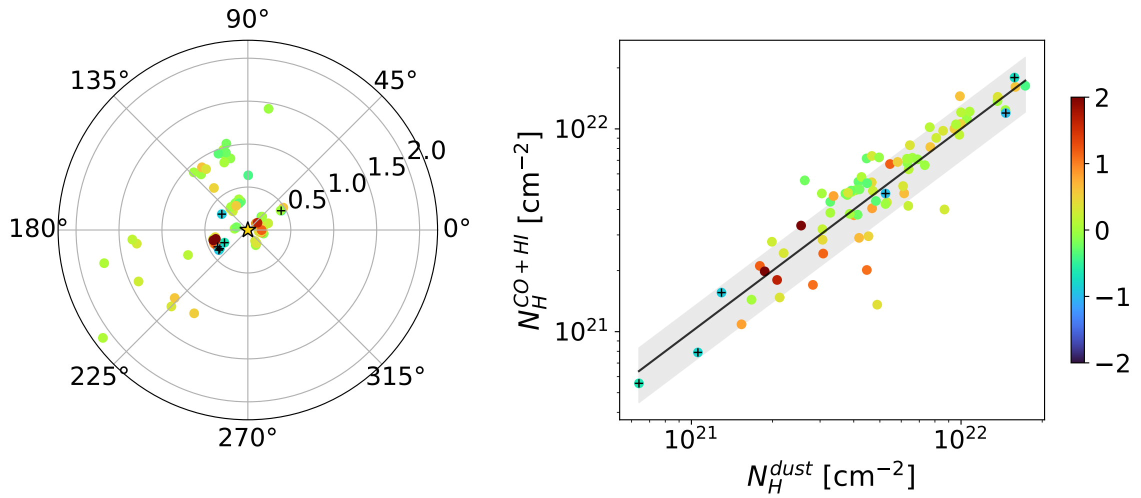

Figure 3: Color map of the relative difference between the detected emissivity and the direct emissivity for each cloud. In the right panel, the clouds are plotted in the (l, d) plane; in the left panel they are plotted in the $N_H^{CO+HI} - N_H^{dust}$ diagram (cfr. Fig 1). Clouds for which we don't have a detection are marked with a black cross.

density in the two derivations, as shown in the right panel of figure 3 , suggesting that this variation is independent of the mass estimation.

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