Giant Molecular Clouds as probes of of Galactic Cosmic Rays with *Fermi*-LAT

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Abstract. Direct measurements of Cosmic Rays (CRs) can not extend much further than the Solar System. In order to probe the so-called "sea" of Galactic Cosmic Rays, one should rely on secondary emission. Gamma rays produced in the interstellar gas, when hit by high energy particles, trace the energy distribution of the parent CRs. Giant Molecular Clouds, being huge reservoirs of hydrogen, serve as perfect targets for interaction with CRs. The high particle density in these objects enables to have enhanced γ emission from small isolated location, and hence to derive information about single spots of the Milky Way. We analyzed more than 9 years data of *Fermi*-LAT from 18 molecular clouds, located in different regions from 100 pc to more than 10 kpc from us, allowing us to have the most comprehensive study on Galactic Cosmic Rays from Molecular Clouds ever.

Cosmic Rays (CRs) in the Galaxy diffuse through the interstellar magnetic fields and spread in the Galactic Disk. The confinement time of these relativistic particles is approximately of 10^7 years for GeV-particles and decreases with energy as $E^{-\delta}$, with $\delta \sim 0.5$. The typical lifetime of accelerators is much shorter, so that CRs have time to propagate and mix uniformly in the Milky Way. For this reason, we expect to find the same energy density and spectrum, essentially a *sea*, of CRs, almost everywhere in the Galaxy. Exceptions may occur in the vicinity of an accelerator, where freshly injected particles can cause an excess over the 'sea' typical density.

The diffuse γ-ray emission in the Galactic Disk is produced by interaction of CRs with the interstellar medium and therefore contains information about the spatial and energy distributions of these particles. γ-ray photons reach the Earth undeflected from the region where they were produced and their detection allows us to trace back their parent particles distribution. In particular in the energy range from 1 GeV and above, one of the main channels of production of γ-s comes from decay of neutral pions, produced by interaction of high energy protons with protons of the interstellar gas [1, 2]. Remarkably, where the proton density is high, as in the case of molecular clouds ($\sim$100 cm^{-3}), this

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process dominates [3]. Detection of this γ radiation provides direct information about the parent proton spectrum as $F_\gamma \propto n_H \cdot \rho_{CR}$. Different studies on the diffuse emission of the Galactic Disk [4, 5] showed that the CR density is not constant throughout the plane, but instead is enhanced in the ring within 4 and 6 kpc from the Galactic Center (GC). That effect could be explained by considering that the analyzed emission is an average on a region that contains a higher number of potential accelerator, or that it could be enhanced because of the contribution of numerous weak unresolved sources. To have a comprehensive understanding of the CR distribution, and to actually test the CR sea, one should probe different specific locations in the Galaxy. Giant Molecular Clouds (GMCs), being huge reservoirs of protons ($M \sim 10^5 - 10^7$ M$_\odot$), concentrated in a small radius (10-100 pc) enable this kind of investigation. In these regions the particle density is by order of magnitudes higher than the average density of the interstellar medium. For this reason, the probability of interaction of cosmic protons with the gas is bigger in GMCs and consequently the γ-ray flux from these objects is enhanced. On the other hand MCs are often the dominant objects, in terms of gas, in one specific direction. In some cases the emission of a single cloud could represent even the 80%, or more, of the entire emission of the line of sight and it is possible then to identify, with a certain precision, the origin of the emission with the position of the cloud. Measuring γ-rays from isolated MCs, permits to derive the CR distribution in the cloud ambient and therefore they are special, if not the sole, targets that could serve as CR barometers throughout the Galaxy [6, 7].

In the case of MCs the emitted flux in γ-rays depends on the column density of the cloud, usually expressed in terms of the ratio M_5/d_{kpc}^2 (with M_5 and d$_{kpc}$ the mass and the distance expressed in units of 10^5 M$_\odot$ and kpc, respectively). Consequently, detection is possible if clouds are sufficiently massive, or very close. A value of $M/d_{kpc}^2 \sim 1$ is ideal for *Fermi*-LAT, but this threshold could be significantly decreased, when considering small objects in uncrowded regions. So far, this study has been successfully applied to clouds of the near (few hundred parsecs) Gould Belt region [8–10], and to Sagittarius B2 [11], a very massive (~150 M$_\odot$) molecular cloud, close to the Galactic Center. In order to probe the CR sea, one needs to have the highest possible number of targets, and preferably located in many different regions. In this work we focused on different environments from the near Gould Belt region to the inner Galaxy . We considered the clouds listed in ref. [12] as they provide a new improved estimation of the distance of these objects . Among all we chose to reanalyze three clouds of the Gould Belt, as they are representative of the local (~ 200 pc) environment, and cross-checked our methods with former results. We included in the analysis Lupus, that was not studied before, and we performed a new analysis on Taurus and Orion A, by taking advantage of the new improved statistics. From the same list we picked three other objects that stand outside the Gould Belt system, at a distance from 0.8 kpc to more than 2 kpc, We then looked at the recent catalog of ref. [13] that contains 1064 objects spread in the entire Galactic Disk, several of them with masses exceeding 10^6 M$_\odot$. From this catalog we selected 10 good candidates for the *Fermi*-LATanalysis located from 600 pc to 12 kpc from us. All chosen clouds have a parameter $M_5/d_{kpc}^2 \gtrsim 0.4$, they are the dominant object on the gas L.o.S and they are not overlapping with known γ-ray sources. This allows us to obtain high quality results and to precisely localize the origin of the gamma radiation with the position of the cloud.

We analyzed *Fermi*-LAT data accumulated for more than nine years, from MET 239557417 (4th August 2008) to MET 533045411 (22nd November 2017). We put a lower energy threshold at 800 MeV, to take advantage of the better angular resolution and to reduce the source confusion. We considered PASS8 data and selected 'FRONT+BACK' events (`evtype=3`). We cut in zenith angles (z$_{max}$=90°), to avoid the Earth limb events and imposed `DATA QUAL==1 && LAT CONFIG==1`. The considered ROI was a 10°x10° square, around the cloud centre. For each molecular cloud under analysis we created a spatial template derived from the CO radio-maps of ref. [14]. As spectral model, we assumed a PowerLaw and left normalization and spectral index free. As template for the background, we could not make use of the standard galactic background model provided by the *Fermi*-LAT collaboration [5], since the emission from the molecular clouds is included there as background. We built then a customized background model, by considering the main channels of production of γ rays above 1 GeV: π^0-decay emission, inverse Compton scattering and extra-galactic diffuse. We created a spatial template of the π^0-decay emission by considering the gas map of HI [15] and CO [14], from which we excluded the cloud; we assumed a PowerLaw spectrum and freed normalization and index. For what concerns the Inverse Compton scattering, we took the map of `galprop v.54` [16] and we derived the isotropic extra-galactic component by fitting a region at high latitude in the outer galaxy, where the galactic contribution is minimum. We included in the model also the sources from the 3FGL catalog [17].

For the first time CR spectra has been successfully extracted from specific regions of the Milky Way. The entire discussion of the results is left to the main paper [18]. Preliminary results from many different locations are in good agreement with theoretical assumption that the CRs embedded in the clouds regions are characterized by the same spectrum as the locally measured one, reported by the AMS collaboration [19]. Deviations are measured only in the inner Galaxy, where we see in general an enhanced flux, as observed in ref. [4, 5]. The heterogeneity of the derived parameters anyhow suggests that flux variation depends on local factors as the vicinity to a specific accelerator. On the other hand, CR spectra measured in the outer Galaxy perfectly agrees with AMS02 data [19]. Our independent analysis based on 9 years of *Fermi*-LAT data of the Gould Belt clouds confirms what found in previous work [9, 10], but our wider sample of clouds give new strength to the hypothesis of a general 'sea' level of galactic cosmic rays . In particular the spectral parameter extracted in regions beyond 2 kpc from the Earth, are in good agreement with the locally measured parameters, suggesting that the behaviour of CRs has a more general character, and is not influenced by local factors. This remarkable constancy of the derived densities and the spectral indices of CRs suggests that we are dealing with the sea of CRs.

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