The contribution of unresolved sources on the gamma-ray spectrum of molecular clouds

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Abstract. Fermi-LAT observations of the large-scale diffuse gamma-ray emission unveiled that in some locations, towards the inner Galaxy, the spectrum of this component is harder than the local one, measured at the Earth position. If this signal is associated with the "truly" diffuse emission produced by the interaction of cosmic rays (CRs) with the interstellar medium (ISM) then its observed spectral features can be interpreted as indirect evidence of a CR spectral hardening toward the Galactic center. However, in order to correctly interpret the data, the contribution from unresolved sources has to be taken into account. Newly developed theoretical models showed that the cumulative flux produced by unresolved pulsar wind nebulae (PWNe) added to the "truly" diffuse emission significantly shapes the spectrum of the large-scale diffuse emission, challenging the CR spectral hardening hypothesis. In light of the recent results, we discuss the effect of unresolved PWNe on the observed spectra of the diffuse emission with a particular focus on molecular clouds (MCs). We analyze the influence of unresolved sources on clouds of different sizes and locations. Finally, we provide a prescription on how to choose the regions to target in order to have an unbiased determination of the "truly" diffuse emission.

1 Introduction

Galactic diffuse emission in the GeV energy band is mostly produced by the interaction of CR nuclei with the dense ISM. Observations of this radiation bring priceless information on the spatial and spectral distribution of CRs in the Galaxy far from the Solar System.

Gamma-ray astronomy has been extensively used to probe the CR spectrum across the Galaxy targeting both the large-scale diffuse emission (e.g. [1]) and MCs [2, 3]. These observations showed an enhanced gamma-ray emission and harder spectrum around ~ 4 kpc, compared to what is measured at Earth. The causes for this deviation are still unclear. This finding was interpreted as evidence of a progressive CR spectral hardening towards the Galactic center. Nevertheless, the inferred CR spectral index from known MCs shows a significant variation within the same ambient [2, 3]. These fluctuations could be related to the higher density of CR sources in the enhanced ring. The presence of nearby sources would significantly change the gamma-ray emissivity depending on the relative distance cloud/accelerator(s).

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Another possible explanation involves faint sources that produce a flux that does not overcome the detection threshold. These unresolved sources constitute a non-negligible component that adds to the "truly" diffuse emission, namely the one contributed by the bulk of CRs interacting with the ISM, and shapes the measured large-scale diffuse emission. In previous studies, their contribution was considered relevant only at very high energy ($\gtrsim$ 1 TeV) and was constrained to be less than 20% at GeV energies [1]. However, these results were obtained disregarding the contribution of PWNe. Recently, it was demonstrated that unresolved PWNe can shape the spectrum of the large-scale diffuse gamma-ray emission probed by Fermi-LAT in the GeV energy range and eventually explain the CR spectral hardening observed in the inner Galaxy [4].

In this work, we investigate the influence of such a component on the observed gamma-ray spectra from MCs. Being the unresolved source contribution subject to the observed angular size, we expect it to be less important when observing smaller regions. If compact clouds are unaffected by this additional diffuse signal, that would make them an unbiased barometer to probe the CR density in the Galaxy.

2 Methods and results

We calculated the expected diffuse contribution from MCs according to:

$$F_\gamma = N_{col}\Delta\Omega\,\xi_N \int dE_p \frac{d\sigma(E_p, E_\gamma)}{dE_\gamma} J_p(E_p, \bar{r}_{MC}) \propto \frac{M_5}{d_{kpc}^2}\xi_N \int dE_p \frac{d\sigma(E_p, E_\gamma)}{dE_\gamma} J_p(E_p, \bar{r}_{MC})$$

where N_{col} is the column density of the gas, $\Delta\Omega$ is the angular size covered by the MC, ξ_N accounts for the fraction of heavy nuclei in the CRs and in the ISM, $d\sigma/dE_\gamma$ is the proton-proton differential cross section and $J(E_p, \bar{r}_{MC})$ is the flux of protons at the location of the interaction; M_5 is the mass of the MC in units of 10^5 $M_\odot$ while d_{kpc} is the distance from us in kpc. In the following, we assumed both a CR spectrum that matches the local measurements, as modeled in [5], and a harder CR spectrum of index 2.5, normalized to the local measurements. In this analysis, we focus on the specific region centered at $(l, b) = (330, 0)^\circ$ for different possible $\Delta\Omega$. This region has been chosen because it overlaps with the position of a well-known MC from the catalog of [6] and because, at this location, the contribution from unresolved sources (modeled as in [4]) is maximized and eventually emerge above the truly diffuse signal as a combined result of the source spatial distribution and the gas distribution. In the above estimate, the truly diffuse emission is calculated for our two hypotheses on the CR spectrum by assuming the target gas as traced by Planck opacity measurements at 353 Hz. The ratio between the unresolved and the truly diffuse components is shown in Figure 1 for the different spectral assumptions and as a function of energy. As expected, the influence of unresolved sources increases with energy and with the angular size. As clouds in the Galaxy, with the exception of local clouds, are $\lesssim 1^\circ$ extended (rightmost panel of Fig. 1), the flux of unresolved sources is expected to be less than 30% even where the unresolved contribution peaks. To test the above observation, we perform the Fermi-LAT analysis at the MC location $(l, b) = (333.4, 0.4)^\circ$ following the methods of [3] to extract the spectrum of the cloud and of the surrounding (10-deg wide) medium. In addition to the standard sources from the Fermi-LAT catalog, we include in the model the upper limit and the lower limit of the unresolved component, as derived by [4]. We extract the spectrum in the hypothesis of low, high, and no contribution of unresolved sources.

The results are shown in Fig. 2. In the case of the cloud, no variation of the spectral points is detected in the different cases, therefore, the contribution of unresolved sources seems not to affect the chosen cloud. Since it is located in a region where this contribution is maximized and has $\Delta\Omega \sim 1^\circ$ larger than the average angular size of other clouds, we expect

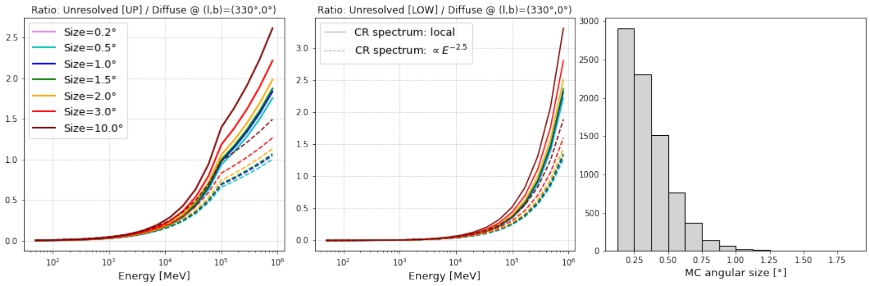

Figure 1. The ratio between the unresolved sources and the truly diffuse emission integrated over different areas. The right-most panel shows the distribution of extensions of MCs in the Milky Way [6]

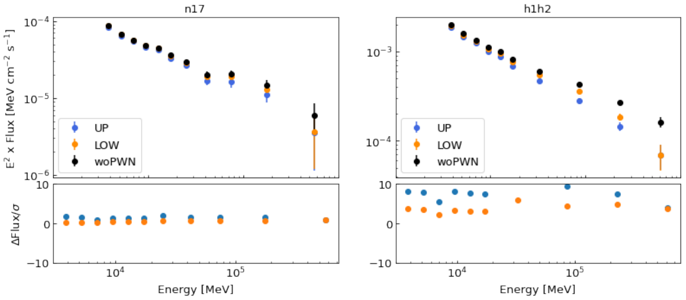

Figure 2. Spectral energy distribution (SED) of the cloud (left) and its surrounding medium (right) obtained including the lower (orange) and upper (blue) limit for the unresolved sources in the model. Black points show the SED obtained without including the unresolved contribution. In the lower panels we show the difference from the spectral points obtained with and without the contribution of unresolved sources in the lower- and upper-limit case, as a fraction of the statistical uncertainty.

that for $\Delta\Omega \leq 1°$ the influence of unresolved component is negligible. This changes when we look at the surrounding area. Here the diffuse emission is modified by the presence of unresolved sources and it shows clearly a harder spectrum when the unresolved contribution is not included. More targets are under analysis to confirm this finding. This will allow us to localize regions in the plane where the truly diffuse emission can be extracted without contamination from unresolved sources and, therefore, constrain the propagation of CRs in the Disk.

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