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# Molecular clouds as cosmic ray laboratories

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**Abstract.** The advent of high sensitivity, high resolution gamma-ray detectors, together with a knowledge of the distribution of the atomic hydrogen and especially of the molecular hydrogen in the Galaxy on sub-degree scales creates a unique opportunity to explore the flux of cosmic rays in the Galaxy. We here present a methodology to explore the cosmic ray flux both in the vicinity and far away from candidate cosmic ray sources.

**Key words.** Gamma rays: ISM – ISM: cosmic rays – ISM: supernova remnants

## 1. Introduction

One hundred years after their discovery by the Austrian physicist Victor Hess, the origin of cosmic rays (CRs) is still unclear. Diffusive shock acceleration in supernova remnants (SNRs) is the most widely invoked paradigm to explain the Galactic cosmic ray spectrum. The direct observation of cosmic rays from the candidate injection sites is not possible since CRs escape the acceleration sites and eventually propagate into the Galactic magnetic fields. During timescales of about $10^7$ years the particles diffuse in the Galaxy and contribute to the bulk of Galactic cosmic rays known as cosmic ray background or CR *sea*, losing the information on the original acceleration locations and spectra. The information on the locations of individual CR sources, their spectra and their injection rate can be traced back through the gamma-rays which cosmic rays radiate when they interact with the ambient gas in the interstellar medium. In fact, in the inelastic collisions of cosmic rays with the ambient gas, neutral pions are produced, which immediately decay into gamma rays. The resulting gamma radiation is therefore a direct footprint of the parental cosmic ray population (Montmerle 1979; Issa & Wolfendale 1981; Aharonian 1996).

In Section 2 we will describe a methodology to investigate the CR flux and spectrum in distant regions of the Galaxy from observations of gamma-rays emitted by CRs propagating through molecular clouds far from known CR sources. In Section 3 we will present the results of the modeling of the gamma-ray emission in molecular clouds close to young SNRs. Our conclusions are given in Section 4.

## 2. Molecular clouds as Cosmic Ray Barometers

We here describe a methodology which uses the emissivity of molecular clouds located far away from CR sources, so called *passive* molecular clouds, to probe the level of the CR background.

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We start by evaluating the longitudinal profile of the emission from the region of interest in the Galaxy under the assumption that the CR flux in that region is equal to the locally observed CR flux. The predicted longitudinal profile of the gamma-ray emission due to protons scattering off the atomic (Kalberla et al 2005) and molecular hydrogen (Fukui et al 1999, 2001) from the region which spans Galactic longitude $340° < l < 350°$ and Galactic latitude $-5° < b < 5°$ is shown in Figure 1 (*Top*). A peak in the emission at longitude of about 345.7° close to the Galactic Plane is clearly visible, next to a dip in the longitude profile. While the atomic gas is generally broadly distributed along the Galactic Plane, the molecular hydrogen is less uniformly distributed and the peaks in the $\gamma$-ray longitude profiles correspond to the locations of highest molecular gas column density. The peaks in the longitudinal profile reveal the directions in the Galaxy where massive clouds associated with spiral arms are aligned along the line of sight. Fig. 1 (*Bottom*) shows that the peak in the $\gamma$-ray emission from the direction 345.7$^o$ close to the Galactic plane is mostly produced within 0.5 kpc and 3 kpc distance from the Sun (in fact 85 percent of the emission is produced in a region within 0.5 kpc and 3 kpc distance from the Sun). Thus the $\gamma$-ray emission from this direction provides a unique probe of the CR spectrum in 0.5-3 kpc (Casanova et al 2010a). Given that the gamma-ray-emission from the molecular cloud depends only upon the total mass of the cloud, M, and its distance from the Earth, $d$, the CR flux, $\Phi_{CR}$, in the cloud is uniquely determined as

$$\Phi_{CR} \propto \frac{F_\gamma d^2}{M}, \qquad (1)$$

where $F_\gamma$ is the integral gamma-ray flux from the cloud. Under the assumption that the CR flux in the cloud is equal to the locally observed CR flux, the predicted $\gamma$-ray flux from the cloud can be compared to the observed gamma-ray flux in order to probe the CR spectrum in distant regions of the Galaxy. The detection of under-luminous clouds with the respect to predictions based on the CR flux at Earth would suggest that the local CR density is enhanced with respect to the Galactic average density. This would cast doubts on the assumption that the local CRs are produced only by distant sources, and that the CR flux and spectrum measured locally is representative of the average Galactic CR flux and spectrum.

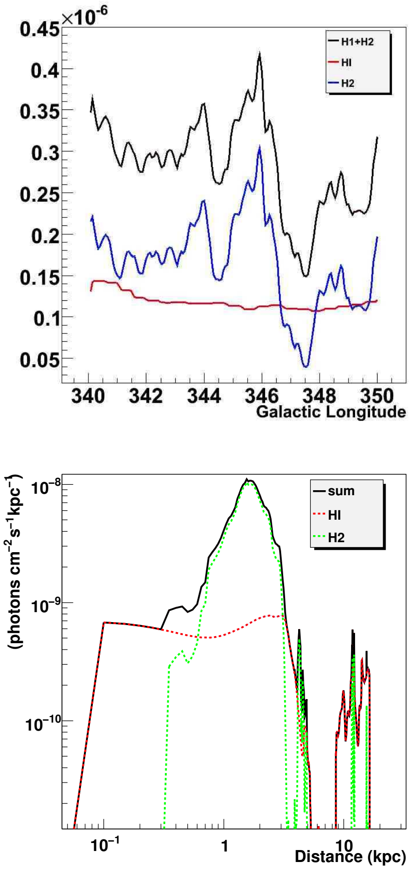


**Fig. 1.** (*Top*)The longitudinal profile of the $\gamma$-ray emission from the region $340^o < l < 350^o$, integrated over the latitude range $-5^o < b < 5^o$. The dotted green lines are for the emission arising from CRs scattering off molecular hydrogen, the dashed red ones for the emission arising from CRs scattering off atomic hydrogen and the solid black ones for the sum. (*Bottom*) Flux above 1 GeV as function of the line of sight distance, produced by CRs interacting with the atomic and molecular gas. (Casanova et al 2010a)

## 3. Gamma ray emission from runaway CRs

Cosmic rays escaping supernova remnants diffuse in the interstellar medium and collide with the ambient atomic and molecular gas (Montmerle 1979; Issa & Wolfendale 1981; **?**). From such collisions gamma-rays are created, which can possibly provide the first evidence of a parent population of runaway cosmic rays. Quantitative predictions of the morphology and of the spectra of the gamma-ray radiation close to CR sources can be obtained by conveying all information on the enviroment, the source age, the acceleration rate and history. Such detailed morphological and spectral predictions can be compared to observations and be used to unveil CR sources.

Detailed modeling of the energy spectra and of the spatial distribution of the gamma-ray emission in the environment surrounding RX J1713.7-3946 have been presented by using the data from atomic and molecular hydrogen surveys. It turns out that the $\gamma$-ray spectra close to CR sources show a peculiar concave shape, being soft at low energies and hard at high energies (Casanova et al 2010b). Figure 2 shows the predicted gamma-ray spectra from hadronic interactions of background and runaway CRs in four regions around the SNR RX J1713.7-394 (Casanova et al 2010b). In all four locations the hadronic gamma-ray emission is enhanced with respect to the hadronic emission due only to background CRs at energies above few TeVs as a consequence of the fact that the CR fluxes are enhanced above 100 TeV. CRs of about 100 TeV are, in fact, thought to be released now by RX J1713.7-394 (Zirakashvili, V.N. & Aharonian 2010). In the three regions a, b and d the high energy emission is clearly dominated by the radiation produced along the line of sight distance between 900 and 1100 parsecs, plotted in dashed lines in Figure 2 . The gamma-ray emission from high latitude regions, such as region c, is instead dominated by the contribution from IC scattering of background electrons, almost at all energies. In regions closer to the Galactic Plane the emission from inverse Compton scattering of background electrons is subdominant

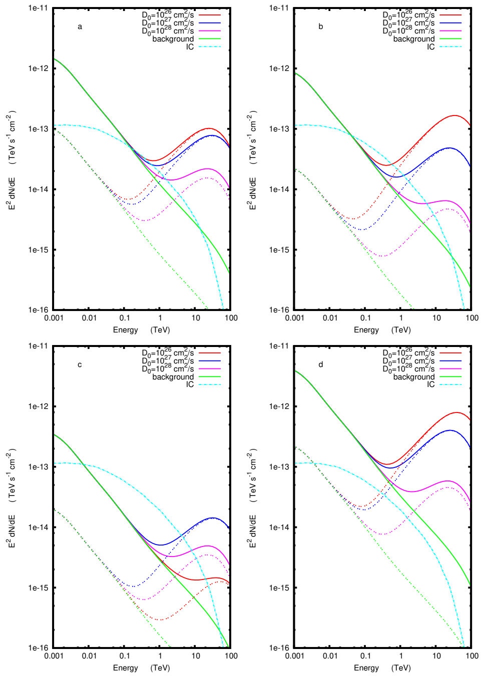


**Fig. 2.** The $\gamma$-ray energy flux in four different regions of $0.2 \times 0.2$ degrees around the positions a = (346.8, -0.4), b = (346.9, -1.4), c = (347.1, -3.0) and d = (346.2, 0.2). The emission produced along the line of sight distance between 900 and 1100 parsecs is plotted in dashed lines, while the emission obtained by summing the radiation contributions over the whole line of sight distance, from 50 parsecs to 30000 parsecs, is shown in solid lines. The emission in the panels a,b,c and d, corresponding to the different locations, is plotted for different diffusion coefficients $D_0$. The emission from background CRs is also shown in each panel for comparison. The contribution to the emission from inverse Compton scattering of background electrons is indicated with a dashed light blue line.

at TeV energies, where runaway cosmic rays produce the enhanced emission. Therefore the regions where to look for the emission from runaway particles are low latitude regions of higher gas density.

Figure 3 shows the ratio of the hadronic gamma-ray emission due to total CR spectrum to that of the background CRs for the entire region under consideration. In our modeling only CRs with energies above about 100 TeV have

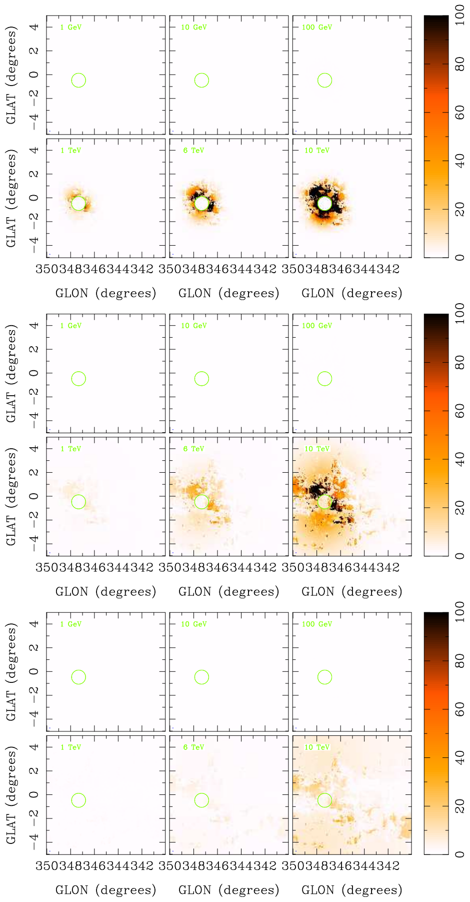


**Fig. 3.** Ratio of the emission due to the sum of background CRs and runaway CRs and background CRs only. The SNR is supposed to have exploded at 1 kpc distance from the Sun at 347.3° longitude and −0.5° latitude 1600 years ago and to have started injecting the most energetic protons 100 years after the explosion (Zirakashvili, V.N. & Aharonian 2010). The diffusion coefficient assumed within the region $340^{\circ} < l < 350^{\circ}$ and $-5^{\circ} < b < 5^{\circ}$ is $10^{26}$ cm$^2$/s in the left panel, $10^{27}$ cm$^2$/s in the middle panel and $10^{28}$ cm$^2$/s in the right panel. In the three panels the ratio of the emission is shown for different energies from 1 GeV to 10 TeV.

left the acceleration site (Zirakashvili, V.N. & Aharonian 2010) and the morphology of the emission depends upon the energy at which one observes the hadronic gamma-ray emission. The hadronic gamma-ray emission and the ambient gas distribution are correlated if and only if the parent CRs have already been released by the SNR and had time enough to diffuse into the ISM. The different spatial distribution of the emission is also due to the different energy-dependent diffusion coefficients, assumed in the three different panels, making it into a useful tool to investigate the highly unknown CR diffusion coefficient (Casanova et al 2010b; Casanova 2011).

## 4. Conclusions

We have presented a methodology to test the cosmic ray flux in discrete distant regions of the Galaxy by comparing the predicted and the measured gamma-ray flux from dense MC regions, close and far away from candidate cosmic ray sources. In particular, detailed modeling of the energy spectra and of the spatial distribution of the gamma-ray emission in the environment surrounding RX J1713.7-3946 have been presented by using the data from atomic and molecular hydrogen surveys.

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