Modeling the Gamma-Ray Emission Produced by Runaway Cosmic Rays in the Environment of RX J1713.7–3946

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Received 2010 March 15; accepted 2010 May 27

Abstract

Diffusive shock acceleration in supernova remnants is the most widely invoked paradigm to explain the Galactic cosmic ray spectrum. Cosmic rays escaping from supernova remnants diffuse into the interstellar medium and collide with the ambient atomic and molecular gas. From such collisions gamma-rays are created, which can possibly provide the first evidence of a parent population of runaway cosmic rays. We present model predictions for the GeV to TeV gamma-ray emission produced by the collisions of runaway cosmic rays with the gas in the surroundings of the shell-type supernova remnant RX J1713.7–3946. The spectral and spatial distributions of the emission, which depend upon the source age, the source injection history, the diffusion regime, and the distribution of the ambient gas, as mapped by the LAB and NANTEN surveys, are studied in detail. For the surrounding region of RX J1713–3946 in particular, we find out that it depends on the energy band one is observing whether one may observe startlingly different spectra or may not detect any enhanced emission with respect to the diffuse emission contributed by background cosmic rays. This result has important implications for current and future gamma-ray experiments.

Key words: gamma rays: theory — ISM: clouds — ISM: cosmic rays — ISM: supernova remnants

1. Introduction

Cosmic rays (CRs) are the highly energetic protons and nuclei which fill the Galaxy and, at least in the vicinity of the Sun, carry as much energy per unit volume as the energy density of starlight or of the interstellar magnetic fields, or the kinetic energy density of the interstellar gas.

Sources of CRs of energies up to the “knee” (10^{15} eV), or even up to 10^{18} eV, are believed to be located in the Galaxy. Galactic CRs are thought to be accelerated via diffusive shock acceleration (DSA) operating in the expanding shells of supernova remnants (SNRs) (see, e.g., Blandford & Eichler 1987; Malkov & Drury 2001). The accelerated CRs interact with ambient gas as a result of inelastic collision, producing neutral pions, which then decay into gamma-rays.

If the bulk of Galactic CRs up to at least PeV energies are indeed accelerated in SNRs, then TeV gamma-rays are expected to be emitted during the acceleration process CRs undergo within SNRs (Drury et al. 1994). Indeed TeV gamma-rays have been detected from the shells of SNRs (Aharonian et al. 2006b; Albert et al. 2007b). However, such observations do not constitute definitive proof that CRs are accelerated in SNRs, since the observed emission could be produced by energetic electrons scattering low energy photon fields. We note, in fact, that gamma-rays are also produced through inverse Compton and bremsstrahlung processes of very highly energetic electrons.

Gamma-rays are also expected to be emitted when the accelerated CRs propagate into the interstellar medium (ISM) (Montmerle 1979; Isa & Wolfendale 1981; Aharonian 1991; Aharonian & Atoyan 1996; Gabici et al. 2009). Before being isotropized by the Galactic magnetic field, the injected CRs produce gamma-ray emission, which can significantly differ from the emission of the SNR itself, and from the diffuse emission contributed by background CRs and electrons, because of the hardness of the runaway CR spectrum, which is not yet steepened by diffusion. The extension of such diffuse sources does not generally exceed a few hundred pc, the scale on which the spectra of the injected CRs can significantly differ from that of the CR background (Aharonian & Atoyan 1996; Gabici & Aharonian 2007; Rodriguez Marrero et al. 2008; Gabici et al. 2009). These diffuse sources are often correlated with dense molecular clouds (MCs), which act as a target for the production of gamma-rays due to the enhanced local CR injection spectrum. Paul, Casséd, and Cesarsky (1976) and Montmerle (1979) have pointed out that SNRs are located in star-forming regions, which are rich in molecular hydrogen. In other words, CR sources and MCs are often associated and target-accelerator systems are not unusual in the Milky Way. In fact, there have been recently claims of detection of gamma-rays in association with dense MCs close to candidate CR sources, both at GeV energies (Abdo et al. 2009c, 2010; Tavani et al. 2010; Castro & Slane 2010) and at TeV energies (Albert et al. 2007a; Aharonian et al. 2008a, 2008b, 2008c).

In order to probe the interaction of the low-energy component of the ambient cosmic ray flux, Montmerle (2009) has recently proposed using millimeter observations to measure enhanced ionization in TeV-bright molecular clouds. On the
other hand, high energy CRs (1 GeV up to PeV energies) interacting with the ambient gas emit gamma-rays. For this reason the high sensitivity, high resolution gamma-ray data from current (HESS, Magic, Veritas, Fermi, and Agile) and future detectors, such as AGIS, CTA, and HAWC (Aharonian et al. 2008d; Hinton & Hofmann 2009), together with the knowledge of the distribution of the atomic and molecular hydrogen in the Galaxy on a subdegree scale are crucial in exploring the flux of high energy CRs close to the candidate CR sources and in pinpointing the long-searched-for sites of CR acceleration.

The gamma-ray radiation from hadronic interactions in regions close to CR sources depends not only on the total power emitted in CRs by the sources and the distance of the source to us, but also on the ambient interstellar gas density, the local diffusion coefficient, and the injection history of the CR source. It is therefore difficult to definitely recognize the site of CR acceleration from gamma-ray observations alone, since very often only qualitative predictions are provided, rather than robustly quantitative predictions, especially from a morphological point of view. In order to fully exploit the present and future experimental facilities and to test the standard scenario for CR injection in SNRs and propagation, we present here model predictions of the spectral and morphological features of the hadronic gamma-rays emission around a candidate for CR source, RX J1713.7–3946, by constructing as quantitative models as possible. In particular, we will convey all the information concerning the environment, the source age, the acceleration rate, and the history, which all play a role in the physical process of CR injection and propagation. Based on the modeling of the broadband emission from MCs close to CR accelerators developed in Gabici, Aharonian, and Casanova (2009) and on the analysis of the CR background discussed in Casanova et al. (2009, hereafter Paper I), we compute the expected gamma-ray emissivity from hadronic interactions of runaway CRs for the region of $340^\circ < l < 350^\circ$ and $-5^\circ < b < 5^\circ$, assuming that a historical SNR event occurred in 393 A.D. at the location of the SNR RX J1713.7–3946 (Wang et al. 1997).

RX J1713–3946 is thought of as the best example of a shell-type SNR, for which the multiwavelength data suggest that hadronic CR particle acceleration is active up to at least 100 TeV (Aharonian et al. 2006b). The acceleration site within RX J1713.7–3946 is spatially coincident with the sites of nonthermal X-ray emission, and brightening and decay of the X-ray hot spots on a one-year timescale have been detected (Uchiyama et al. 2007). The observed rapid variability of the X-ray emission provides strong evidence for the amplification of the magnetic field around the SNR shell, which is a key condition for the acceleration of protons beyond the 100 TeV limit set by Lagage and Cesarsky (1983). The multiwavelength analysis of the emission from RX J1713.7–3946 supports therefore the hypothesis that CRs up to the knee are accelerated in SNRs. However, no compelling evidence for the acceleration of protons and nuclei to PeV energies has been found until now. Also, even the most energetic CRs cannot be confined for long time within the SNR, and even if RX J1713–3946 might have accelerated particles to $\sim$ PeV once, such highly energetic protons have already left the source. In fact, these very highly energetic particles, which are released first from SNRs and diffuse faster than lower energy CRs, reach first the surrounding clouds of the injection sites and produce enhanced gamma-ray emission. This is the reason why studies of the gamma-ray emission from environment surrounding RX J1713–3946, such as the one presented here, are important.

In section 2 we briefly describe the results of the Leiden/Argentine/Bonn (LAB) survey of the Galactic atomic hydrogen and the NANTEN survey of the Galactic molecular clouds. Section 3 is dedicated to the description of the model. The predictions of the model for the emission from the region under consideration are presented in section 4, where we also discuss the observational prospects for present and future observatories. Our conclusions are given in section 5.

2. Survey Data

The distributions of atomic and molecular hydrogen in the Galaxy, used in the following calculations, are from the LAB Galactic H I Survey (Karberla et al. 2005) and from the NANTEN Survey (Fukui et al. 1999, 2001, 2003; Fukui 2008), respectively.

The LAB observations of atomic hydrogen were centered on the 1420 MHz ($\lambda$ 21 cm) line with a bandwidth of 5 MHz. The velocity axis extends from $-450$ km s$^{-1}$ to 400 km s$^{-1}$ giving a final velocity resolution of 1.3 km s$^{-1}$. The data combines observations from the three telescopes at a resolution of 0$''$.6 with a final sensitivity of $\sim$ 0.1 K.

The NANTEN instrument is a 4 m millimetre/submillimetre telescope, which has surveyed the southern sky, using the $^{12}$CO ($J = 1–0$) emission line at 115.271 GHz ($\lambda = 2.6$ mm). The survey was performed with an angular resolution of 4$''$, with a mass sensitivity of $\sim$ 100 $M_\odot$ at the Galactic center (GC) and 1 km s$^{-1}$ resolution in velocity. The column density of molecular hydrogen is obtained from that of CO by assuming the conversion factor, $X$, to be

$$X = 1.4 \times 10^{20} e^{(R/11kpc)} [\text{cm}^{-2} \text{K}^{-1} \text{km}^{-1} \text{sr}].$$  \hspace{1cm} (1)

where $R$ is the distance to the GC (Nakanishi & Sofue 2003, 2006).

The survey data-cubes of both atomic and molecular hydrogen, given in longitude, latitude, and velocity, are transformed into data-cubes in longitude, latitude, and heliocentric distance by using a flat rotation curve model of the Galaxy with uniform velocity equal to 220 km s$^{-1}$ (Nakanishi & Sofue 2003, 2006). In figure 1 the three dimensional gas distribution (sum of the atomic and molecular gas) in the region which spans Galactic longitude $340^\circ < l < 350^\circ$, Galactic latitude $-5^\circ < b < 5^\circ$, and heliocentric distance 100 pc $< l_d < 30$ kpc is shown. For detailed discussions of the data and its limitations and errors, we refer the reader to Paper I.

3. The Model

We have modeled a supernova (SN) of total energy $E_{SN}$, which has exploded into the ISM in the region of the Galaxy described above. Our SNR that is identifiable with the historical SNR RX J1713.7–3946 is located at a distance of 1 kpc from the Sun and has the same coordinates as
and E RX J1713.7

No. 5] Gamma-Ray Emission in the nearby RX J1713.7−3946

The maximum injection energy in equation (2) is assumed to be $E_{p_{\text{max}}}$. In equation (3), $R_d$ is the diffusion distance for a CR of energy $E_p$.

$$R_d = \sqrt{4D(E_p)[t - \chi(E_p)]}$$

(4)

where $\chi(E_p)$ is the time after the SN explosion at which a proton of energy $E_p$ escapes the injection source and begins to diffuse into the ISM. We also assume that the CRs released by the SNR have an energy-dependent diffusion coefficient,

$$D(E_p) = D_0 \left(\frac{E_p}{10 \text{ GeV}}\right)^{0.5} \text{cm}^2\text{s}^{-1}.$$  

(5)

We take $D_0$ to be $10^{26}$, $10^{27}$ and $10^{28}$ cm$^2$ s$^{-1}$. The diffusion of CRs into molecular clouds depends upon a highly uncertain diffusion coefficient. It is thought that CRs can penetrate through clouds if the diffusion coefficient inside the cloud is the same as the average one in the Galaxy, as derived from spallation measurements. CRs are effectively excluded if the diffusion coefficient is suppressed compared to the surroundings. However, it has been shown that CRs at TeV energy can diffuse into even the densest parts of molecular clouds, whilst those at GeV might have trouble in penetrating through the densest parts (Gabici et al. 2007, 2009; Protheroe et al. 2008; Jones et al. 2009).

3.1. Hadronic Gamma-Ray Emissivity

The hadronic gamma-ray emissivity, which is given as the gamma-rays produced by CRs interacting with the gas per centimeter, per second, and per GeV at a position defined by its coordinates, $(l, b)$, and the heliocentric distance, $l_d$, can be expressed as

$$e\gamma(E_{\gamma}, l, b, l_d) = \frac{dN_{\gamma}}{dVdlE_{\gamma}}dt = \int_{E_{p_{\text{th}}}}^{E_{p_{\text{max}}}} \frac{dE_p}{dE_{\gamma}} d\sigma_{p_{\gamma}}(E_p, E_{\gamma}) \times c n(l, b, l_d) \rho_{\text{CR}}(E_p, l, b, l_d).$$  

(6)

where the integral is calculated over the energy, $E_{\gamma}$, of the protons, $E_{p_{\text{th}}}$ is the minimum proton energy that contributes to the production of a photon of energy $E_{\gamma}$. In equation (6) the spectral dependence of the photons emitted by CR protons, expressed in terms of the differential cross section, $d\sigma_{p_{\gamma}}/dE_p$, can be calculated by using the simple but precise parametrization developed by Kelner, Aharonian, and Bugayov (2006). However, at low energies when a wide variety of proton spectra are expected, we use the parametrization by Kamada et al. (2006). In equation (6) $c$ is the velocity of light and $n(l, b, l_d)$ is the ambient gas density as a function of $b, l$, and $l_d$. $\rho_{\text{CR}}(E_p, l, b, l_d)$ is the proton energy density, which is given by the sum of the background CR density, $\rho_{\text{bg}}(E_p)$, and the density of cosmic rays released by the SNR and diffusing into the ISM, $\rho_{\text{SNR}}(E_p, l, b, l_d)$, as given in equation (3).

$$\rho_{\text{SNR}}(E_p, l, b, l_d) = \rho_{\text{bg}}(E_p) + \rho_{\text{SNR}}(E_p, l, b, l_d).$$  

(7)

The CR background spectrum is equal to the CR flux measured
at the top of the Earth’s atmosphere. Below $10^6\text{GeV}$ we here adopt the value of
\[
\Phi_{bg}(E_p) = 1.8 \left( \frac{E_p}{\text{GeV}} \right)^{-2.7} \text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}\text{GeV}^{-1}, \tag{8}
\]

taken from the Particle Data Group (2008). A change in the spectral index of the measured CR flux is observed above $10^6\text{GeV}$, which we do not consider here since we are only interested in the gamma-ray emission below $100\text{TeV}$. The background CR energy density is then defined as
\[
\rho_{bg}(E_p) = \frac{4\pi}{c} \Phi_{bg}(E_p) \approx 7.5 \times 10^{-10} \left( \frac{E_p}{\text{GeV}} \right)^{-2.7} \text{cm}^{-3}\text{GeV}^{-1}. \tag{9}
\]

A multiplication factor of 1.5 is applied to the CR density in equation (7), which accounts for the contribution to the emission from heavier nuclei both in CRs and in the interstellar medium (Dermer 1986; Mori 1997). We note that recently Mori (2009) has recalculated the multiplication factor obtaining a 20% higher value.

The differential photon spectrum measured at Earth is then obtained by integrating the emissivity $e_p(E, l, b, l_d)$ over the distance along the line of sight, $l_d$,
\[
\frac{dN_p}{dAdE_d/dtd\Omega} = \frac{1}{4\pi} \int_{l_d}^{l_{d\text{max}}} dl_d e_p(E, l, b, l_d). \tag{11}
\]

3.2. Leptonic Emission from Primary and Secondary Electrons

Gamma-rays are also produced through inverse Compton and bremsstrahlung processes of very highly energetic primary and secondary electrons and positrons.

A population of primary electrons is accelerated by the SNR and confined within it. The high energy primary electrons suffer, in fact, from strong losses through synchrotron emission, triggered by the amplified magnetic field of the SNR shock, while the low energy part of the primary lepton population cannot escape due to diffusive confinement.

Inverse Compton (IC) scattering of background CR electrons results in a nonnegligible contribution to the overall diffuse gamma-ray emission at GeV energy, and also at TeV, especially at high Galactic latitudes. At low latitudes the relative contribution of this component, compared to the bremsstrahlung and $\pi^0$-decay gamma-rays from specific dense regions, is significantly reduced because of the enhanced gas density. Following Aharonian and Atoyan (2000) in figure 5 we show the contribution to the emission due to IC scattering of background electrons to the emission spectra. The ratio of luminosities from nonthermal bremsstrahlung to hadronic gamma-rays does not depend on the ambient gas density. However, the contribution of the bremsstrahlung of background electrons to the total diffuse emission above 1 GeV is rather low, so it can be ignored.

When CRs interact with ambient matter through inelastic collisions, they produce not only neutral pions, but also charged pions. These charged pions decay into secondary electrons, positrons, and neutrinos (see Gabici et al. 2009). Thus, in addition to the gamma-ray emissivity due to neutral pion decay, there will be a simultaneous radio synchrotron component due to the secondary electrons and positrons produced concomitantly with the neutral pions. The secondary leptons will also produce gamma-ray emission through bremsstrahlung and inverse Compton. However, as discussed in Gabici, Aharonian, and Casanova (2009), the contribution of bremsstrahlung and inverse Compton of secondary leptons is negligible and the pion decay emission is dominant in the large energy ranging from GeV to TeV, assuming that the protons have the energy spectrum given by equation (8). The radio emission of primary and secondary electrons in the environments around SNRs is of interest but beyond the scope of this paper, and is not discussed here.

4. Results and Discussion

4.1. The Emission of Background CRs

We first calculate the spatial features of the hadronic gamma-ray emission on the assumption that the CR spectrum in the region of longitude range of $340^\circ < l < 350^\circ$ and latitude of $-5^\circ < b < 5^\circ$ is uniform and equal to the locally observed CR flux. Figure 2 shows the gamma-ray emission at $1\text{TeV}$ from this region arising from the interaction of background CRs, whose spectrum is given in equation (8), with the ambient atomic and molecular hydrogen, as measured by the LAB and NANTEN surveys. The background CR spectrum being uniform, the morphology of the emission reproduces the gas distribution and does not change with energy. In figure 2 the emission at $1\text{TeV}$ is plotted. The blue ring represents a sphere of 10 pc radius (the radial extension of the radio SNR shell) around the location of the SNR RX J1713.7$-$3946. Hereafter, we assume that the CR spectrum within a radius of 10 pc from RX J1713.7$-$3946 is equal to the CR background spectrum, since we are interested in the emission of CRs leaving their injection source but not in the emission produced by the injected CRs within the SNR shell.

4.2. The Emission of Background and Runaway CRs

Figure 3 shows the predicted hadronic gamma-ray emission at $1\text{TeV}$ arising from the sum of background CRs and the runaway CRs (i.e., $\rho_{bg} + \rho_{SNR}$) as given by equation (7) for the diffusion coefficients discussed in section 3. The spatial distribution of the emission depends upon the CR diffusion coefficient, $D_0$. The faster the CRs diffuse into the ISM, the further the enhanced emission extends beyond the linear extent of RX J1713.7$-$3946. However, for very fast diffusion ($D_0 = 10^{28} \text{cm}^2 \text{s}^{-1}$) the very highly energetic runaway protons have already left the region around the SNR.

The shape of the emission depends also upon the assumptions about the SNR injection history. We have namely assumed that the SNR, which is now $\sim 1600$ years old, started to inject the most energetic particles at $t_{\text{Sedov}} = 100\text{yr}$ after the explosion. According to equation (2) this assumption means that the SNR nowadays starts to release CRs with energy $\sim 100\text{TeV}$. CRs with energy lower than $100\text{TeV}$ are still confined in the SNR shell, whereas higher energy particles have already left it. The gamma-ray emission produced by a proton of 100 TeV peaks at around 10 TeV. Roughly speaking,
CRs with a given energy are responsible for hadronic gamma-ray emission which is $\sim$ 10 times less energetic. The assumption that CRs with energy below 100 TeV are still confined in the SNR shell means then that one expects to observe almost no gamma-ray enhanced emission due to runaway protons at energies below a few TeV in the surroundings of the SNR RX J1713.7–3946. The assumption on the injection history of the CR source is therefore crucial in determining the spatial and spectral features of the gamma-ray emission.

One would expect that the gamma-ray emission from molecular clouds illuminated by the CRs injected from nearby CR sources is spatially correlated with the atomic and molecular gas distribution. This is, generally speaking, true. However, one has to take it into account that both the acceleration history of the source and the diffusion timescale are dependent upon the energy. In other words, when considering gamma-ray emission at a given energy from the region around a SNR, one should expect a correlation between the hadronic gamma-ray and the gas distribution if and only if the parent CRs have already been released by the SNR and had time enough to diffuse into the ISM. On the other hand, the environment of a CR source, which is dense with atomic and molecular hydrogen, might nonetheless appear faint at some energies in gamma-rays simply because the parent CRs have not escaped from the injection source nor had time enough to propagate throughout the region near the source.

Figure 4 shows the average CR energy density from four different regions of $0\degree 2 \times 0\degree 2$ around the four positions, $a = (346\degree 8, -0\degree 4), b = (346\degree 9, -1\degree 4), c = (347\degree 1, -3\degree 0)$, and $d = (346\degree 2, 0\degree 2)$. The CR energy densities from these regions are averaged over 200 pc at the distance of around 1 kpc along the line of sight. If the CR energy density is averaged over the whole line of sight for the distance from 50 to 30000 pc, it would be dominated by the energy density of the background. The background CR energy distribution is also

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**Fig. 2.** The gamma-ray energy flux arising from the background CRs, expressed in GeV cm$^{-2}$ sr$^{-1}$ s$^{-1}$ at 1 TeV. The blue ring represents a sphere of 10 pc radius around the location of the SNR RX J1713.7–3946 (the radial extension of the radio SNR shell).

**Fig. 3.** The predicted hadronic gamma-ray energy fluxes at 1 TeV, expressed in GeV cm$^{-2}$ sr$^{-1}$ s$^{-1}$, arising from background CRs and from CRs escaping from the SNR shells if the CR diffusion coefficient, $D_0$, is equal to $10^{26}$ cm$^2$ s$^{-1}$ (upper panel), $10^{27}$ cm$^2$ s$^{-1}$ (middle panel), and $10^{28}$ cm$^2$ s$^{-1}$ (bottom panel). We assume that the SNR started to release the particles of energy 500 TeV 100 yr after the explosion. In the left bottom corner is indicated the angular resolution of the NANTEN survey.
The average CR proton energy density in four different regions of $0''2 \times 0''2$ around the four positions, $a = (346'8, -0''4)$, $b = (346'9, -1''4)$, $c = (347'1, -3''0)$, and $d = (346'2, 0''2)$. The CR density is averaged over 200 pc at the distance of around 1 kpc along the line of sight. The CR energy distributions in the panels (a, b, c, and d) corresponding to the different locations are plotted for different diffusion coefficients $D_0$. The background CR distribution is also shown in each panel for comparison.

Figure 5 shows the gamma-ray spectra from regions a, b, c, and d, if one considers the hadronic emission produced along the line of sight for the distance from 900 to 1100 pc (in dashed lines) and the hadronic emission obtained by summing the radiation contributions over the whole line of sight (in solid lines). The emissions in the panels a, b, c, and d, corresponding to the different locations, are plotted for different diffusion coefficients $D_0$. The emissions from background CRs are 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. For the modeling of the inverse Compton contribution we follow Aharonian and Atoyan (2000).

from region d is particularly enhanced with respect to the hadronic emission from background CRs. This is due to two factors: the enhanced CR flux near the injection source and the high ambient gas density. In the three regions a, b, and d the high energy emission is clearly dominated by the radiation produced along the line of sight for the distance from 900 to 1100 pc, plotted in dashed lines in figure 5. The gamma-ray emission from a high latitude region, such as region c, is instead dominated by the contribution from IC scattering of background electrons, almost at all energies. In the region closer to the Galactic plane the emission from inverse Compton scattering of background electrons is subdominant at TeV energies, where runaway CRs produce the enhanced emission. Therefore, the regions where one should look for the emission from runaway particles are low latitude regions of higher gas density.
The gamma-ray spectra show a peculiar concave shape, being soft at low energies and hard at high energies, which, as discussed in Gabici, Aharonian, and Casanova (2009), might be important for the studies of the spectral compatibility of GeV and TeV gamma-ray sources. The peculiar spectral and morphological features of the gamma-ray due to runaway CRs can be therefore revealed by combining the spectra and gamma-ray images provided by the Fermi and Agile telescopes at GeV and by present and future ground-based detectors at TeV energies. As shown by the surveys of the Galaxy, published by Fermi at MeV–GeV energies (Abdo et al. 2009a), by HESS at TeV energies (Aharonian et al. 2005, 2006a), and by the Milagro Collaboration (Abdo et al. 2007, 2009b) at very high energies, the various extended Galactic sources differ in spectrum, flux, and morphology. However, there is growing evidence for the correlation between GeV and TeV energy sources (Funk et al. 2008; Abdo et al. 2009b). These sources often appear to spectrally and morphologically different in each energy, possibly due to not only the better angular resolution obtained by the instruments at TeV energies, but also the energy dependence of physical processes, such as CR injection and CR diffusion. For this reason it is important to properly model what we expect to observe at different energies by conveying in a quantitative way all information, recognizing that the environment, the source age, the acceleration rate and history, all these things play a role in the physical process of injection and all have to be taken into account for the predictions.

Figure 6 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 \( \sim 100 \text{ TeV} \) have left the acceleration site and the morphology of the emission depends upon the energy at which one observes the hadronic gamma-ray emission. The different spatial distribution of the emission is also due to the different energy-dependent diffusion coefficients, as assumed in the three different panels.

As discussed at length in Paper 1, the distance to the molecular and atomic gas is highly uncertain. The principle uncertainty in the determination of the distance, especially at distances close to the Sun, which is as large as 2 kpc, comes from errors in the accuracy of estimates of radial velocity of gas clouds. Uncertainties in the distance estimates affect also the determination of the conversion factor \( \mathcal{X} \) in equation (1) (Arimoto et al. 1996), by which the emissivity of the CO line is converted to ambient matter density, and the determination of the number density of H\(_2\) molecules from the measured CO intensity. As noted in Paper 1, these uncertainties do not affect the model predictions of the hadronic gamma-ray flux. This is because the hadronic gamma-ray emissivity is proportional to the gas mass and inversely proportional to the distance squared so that the relative errors exactly cancel.

5. Conclusions

CRs escaping from SNRs diffuse into the ISM and collide with the ambient atomic and molecular gas. From such collisions gamma-rays are created, which can possibly provide the first evidence of a parent population of runaway CRs. The gamma-ray radiation from such hadronic interactions in the regions close to CR sources depends not only on the total power emitted in CRs by the sources and the distance of the source to us, but also on the ambient interstellar gas density, the local diffusion coefficient, and the injection history of the CR source. Due to the fact that the emission from gas clouds around SNRs, illuminated in gamma-rays, depends upon many factors, it is difficult to draw a firm conclusion about the nature of such emission. In order to test the standard
scenario for CR injection in SNRs and CR propagation, we have computed the expected hadronic gamma-ray emissivity for the region of $340^\circ < l < 350^\circ$ and $-5^\circ < b < 5^\circ$, assuming that an SN event has occurred in the location of the historical SNR RX J1713.7–3946 in 393 A.D. Detailed modeling of the energy spectra and of the spatial distribution of the gamma-ray emission using the data from atomic and molecular hydrogen in the environment of RX J1713.7–3946 have been presented. These predictions have shown that the age and acceleration history of the SNR, the particle diffusion regime, and the distribution of the ambient gas are all paramount. The emission from the surrounding regions of SNR shells can therefore provide crucial informations on the history of the SNR acting as a CR source and important constraints on the highly unknown diffusion coefficient. Also, depending on the time and energy at which one observes the remnants and the surroundings, one will observe different spectra and morphologies. This has important implications for the current and future generations of gamma-ray observatories. The high sensitivity and high resolution, which will be reached by future detectors, such as AGIS, CTA, and HAWC (see reviews, e.g., Aharonian et al. 2008d; Hinton & Hofmann 2009), makes the detection of the predicted emission possible.

Sabrina Casanova acknowledges the support from the European Union under Marie Curie Intra-European fellowships. The NANTEN telescope was operated based on a mutual agreement between Nagoya University and the Carnegie Institution of Washington. We also acknowledge that the operation of NANTEN was realized by contributions from many Japanese public donators and companies. This work is financially supported in part by a Grant-in-Aid for Scientific Research from the Ministry of Education, Culture, Sports, Science and Technology of Japan (Nos. 15071203 and 18026004, and core-to-core program No. 17004), Japan Society for the Promotion of Science (Nos. 14102003, 20244014, 18684003, and 22540250), and the Mitsubishi foundation.

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