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Systematic search for molecular clouds near supernova remnants as sources of very-high-energy γ-ray emission

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ABSTRACT

Supernova remnants accelerate particles up to energies of at least 100 TeV as established by observations in very-high-energy γ-ray astronomy. Molecular clouds in their vicinity provide an increased amount of target material for proton-proton interaction and subsequent neutral pion decay into γ-rays of accelerated hadrons escaping the remnant. Therefore, these molecular clouds are potential γ-ray sources. The γ-ray emission from these clouds provides a unique environment to derive information on the propagation of very-high-energy particles through the interstellar medium as well as on the acceleration of hadrons in supernova remnants. Current Imaging Atmospheric Cherenkov Telescope systems are suitable to explore a large parameter space of the propagation properties depending on the age of the supernova remnant and the distance between the remnant and the nearby molecular cloud.

In this paper we present our strategy and results of a systematic search for γ-ray emitting molecular clouds near supernova remnants which are potentially detectable with current experiments in the TeV energy range and explore the prospects of future experiments.

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1. Introduction

The sources of Galactic cosmic rays are more than 100 yr after their discovery still a matter of discussion. Prime candidates are supernova remnants for energies up to 10^{15} eV since the 1930s [1] and observations of supernova remnants from the radio up to the very-high-energy (VHE, $E \geq 100\,\text{GeV}$) γ-ray domain proof the existence of accelerated particles up to energies of about 100 TeV at the shells of supernova remnants, see e.g. for observational reviews [2,3]. The origin of the VHE γ-ray emission is, however, for most supernova remnants still not unambiguously identified. It is still not clear whether the observed γ-ray emission is produced by accelerated leptons via Inverse Compton scattering or by accelerated hadrons interacting with the ambient medium and producing γ-rays via proton–proton collision and subsequent neutral pion decay. Recently, pion-decay signatures in the supernova remnants W44 and IC 443 were detected by the *Fermi*-LAT Collaboration [4], which proofs the acceleration of hadrons at supernova remnants up to GeV energies, but evidence is still missing for supernova remnants being the sources of cosmic rays up to the PeV energy range. In the case of W44 γ-ray emission was detected outside the shell of the remnant coincident with ambient molecular clouds [5]. In this scenario the γ-ray emission is produced by hadrons which are accelerated in the shock of the supernova remnant and afterwards escaped the acceleration site. They diffuse in the interstellar medium until a molecular cloud is reached, which represents an increased amount of target material where γ-ray emission is produced via the neutral pion decay.

γ-ray emitting molecular clouds in the vicinity of supernova remnants are therefore promising targets to study the acceleration mechanism of cosmic rays in supernova remnants. In addition these associations can be used to explore the propagation properties of VHE particles which escaped the acceleration region of the remnant and afterwards travelled through the interstellar medium. The W28 region was studied thoroughly in this perspective. TeV γ-ray emission was detected by the High Energy Stereoscopic System (H.E.S.S.) Collaboration in three distinct regions [6] where two coincide with molecular clouds offset from the supernova remnant and one coincide with a molecular cloud at the shock. Two of these regions were also detected in GeV energies by the *Fermi*-LAT Collaboration [7]. Studies of propagation properties, see [8–11], using isotropic diffusion models showed, that the diffusion at 10 GeV is suppressed by more than one order of magnitude compared to the Galactic average value of $\approx 10^{28}\,\text{cm}^2\,\text{s}^{-1}$ [12]. Applying an anisotropic diffusion model to the W28 region [13] resulted in a higher diffusion coefficient in

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the order of 10^{28} cm^2 s^{-1} which is in the same range as the Galactic average value.

Up to now only a few of such associations are observed and identified in TeV γ-rays, therefore we present in this paper a systematic search for promising regions with TeV γ-ray emitting molecular clouds in the vicinity of supernova remnants.

The H.E.S.S. experiment provides with the H.E.S.S. Galactic Plane Survey the largest connected data set in the TeV γ-ray band. It ranges from 250° to 65° Galactic longitude and from −3.5° to 3.5° Galactic latitude. The data set comprises 2800 hours of high-quality data, taken in the years 2004 to 2013. The integral flux sensitivity of the H.E.S.S. Galactic Plane Survey for point sources ranges from 0.5% Crab units (C.U.)[1] to 1.6% C.U. being in large part better than 1.0% C.U. The sensitivity was calculated under the assumption of an energy spectrum following a power law with an index of about −2.3 [14]. The inhomogeneity in the γ-ray flux sensitivity arises from different observation times and varying observation conditions. However, the H.E.S.S. Galactic Plane Survey is very well suited for population studies in general.

In this work, its γ-ray flux sensitivity, along with molecular clouds from the Boston University - Five College Radio Astronomy Observatory (BU-FCRAO) Galactic Ring Survey of ^{13}CO emission [15] is used to search for regions populated with γ-ray emitting molecular clouds. We refer to this catalogue in the following as Galactic Ring Survey. This survey covers the region between 18° and 56° Galactic longitude and between −1° and +1° Galactic latitude [15]. A total of 829 molecular clouds and 6124 clumps have been identified within the data of the Galactic Ring Survey by Rathborne et al. [16]. For our work only the molecular clouds, not the clumps, identified in the Galactic Ring Survey are used. Roman-Duval et al. [17] determined for about 750 molecular clouds of the Galactic Ring Survey the distance to Earth solving the distance ambiguity by looking in neutral hydrogen emission data for self-absorption features. The masses of these molecular clouds have been estimated by Roman-Duval et al. [18]. With the help of this catalogue, the parameters of known supernova remnants and a theoretical model for the prediction of the γ-radiation of the molecular clouds it is possible to perform a general search for γ-ray emitting molecular clouds.

The theoretical model used in this paper is described in Section 2. This is followed by the evaluation of the explorable parameter space of the diffusion coefficient for hadronic particles in the vicinity of supernova remnants with current Cherenkov telescope systems (see Section 3).

2. Basics of γ-ray emission from molecular clouds in the vicinity of supernova remnants

The systematic search is based on the theory, that hadrons are accelerated up to a maximum energy at the shock fronts of supernova remnants. When the particles have reached their maximum energy, which depends on the age of the supernova remnant, the shock radius and the magnetic field, the particles cannot longer be confined within the acceleration site as their diffusion length exceeds the characteristic size of the acceleration region. The particles escape from the supernova remnant, propagate into the interstellar medium and hit eventually a molecular cloud, which represent an increased target material for proton–proton interaction. Among others neutral pions are produced which subsequently decay into γ-rays. There exist several theoretical models to describe these processes and to predict the γ-ray emission from these molecular clouds. They range from simple approaches to complex ones using numerical simulations. In this paper, we aim for a general search which is applicable to a broad variety of supernova remnants and molecular clouds. Therefore we have chosen the model of Gabici et al. [19] which is based on an isotropic propagation model and a parametrisation of the maximum energy dependent on the age of the supernova remnant to estimate the proton density at the location of the molecular cloud. More elaborated models that rely on detailed information on the individual supernova remnant environments, e.g., magnetic field orientations, are not suited for a general search strategy as discussed in this work.

The model of Gabici et al. [19] utilises a phenomenological approach for the maximal reachable energies (and momentum p_{max}) that protons can achieve via the acceleration process. A maximal momentum p_{max} of 5 PeV for a supernova age of 200 yr and of 200 GeV at 5×10^4 yr is assumed with $p_{max} \approx t^{-2.48}$. This results in a distribution function f_e of the escaped particles at a distance R to the remnant, with energies $E \geq c \cdot p_{max}(t)$ at a given time t, of $f_e = (\eta E_{\rm SN})/(\pi^{3/2} \ln(E_{\rm max}/E_{\rm min})) \cdot \exp(-R/R_d)^2/(R_d^3 E^2)$, with $E_{\rm SN}$ the explosion energy of the supernova, η the portion of this energy converted into the acceleration of cosmic rays, $E_{\rm max}$ and $E_{\rm min}$ the maximal and minimal energies of the accelerated particles during the Sedov phase and the diffusion length $R_d = \sqrt{4D(E)(t-\chi(E))}$ of a particle with energy E. $\chi(E)$ gives the time when the particles with energy E escape the acceleration site and $D(E)$ the diffusion coefficient which is parametrised as $D(E) = D_{10} \cdot (D/10\,\mathrm{GeV})^s$ cm^2 s^{-1}. In this model a free penetration of the cosmic rays into molecular clouds is assumed, as it is valid unless there is no significant difference in diffusion coefficient inside and outside the molecular cloud [20] and recent observations of the Orion clouds in the GeV energy range suggest a penetration of the cosmic rays into most of the cloud volume [21]. The calculation of the γ-ray emission due to the neutral pion decay is done using the parametrisation by Kelner et al. [22]. For the total photon flux, as described above, a factor of 1.45 is multiplied to account for the contribution by nuclei heavier than helium present in the interstellar medium [23].

3. Explorable parameter space of the diffusion coefficient with current Cherenkov telescope experiments

As already mentioned in the section above, the particle propagate after escaping the supernova remnant through the interstellar medium. The propagation properties are almost unknown and therefore an interesting task to study them in some more detail. The propagation in the model of Gabici et al. [19] is described by an energy dependent diffusion coefficient. In the following we explore the parameter space of this coefficient detectable with the current generation of Cherenkov telescope arrays dependent on the distance $D_{\rm SNR\text{-}MC}$ between the molecular cloud and the supernova remnant as well as on the age of the supernova remnant.

Exemplarily the γ-ray flux sensitivity of the H.E.S.S. Galactic Plane Survey [14] and the characteristics of the molecular clouds which are identified in the Galactic Ring Survey [16–18] are used. Half of these molecular clouds are located closer to Earth than 5.3 kpc, and these clouds have an average mass of $\approx 3 \times 10^4$ M$_\odot$.

Therefore, the cloud in the example scenario presented in this paper to motivate our search strategy with current experiments is chosen to have a mass of 3×10^4 M$_\odot$ and distance to Earth of 5.3 kpc. In addition a closer distance of the molecular cloud to Earth of 2.5 kpc is evaluated. For the SNR a Sedov time of 150 yr and an efficiency of 30% for the conversion of the supernova explosion energy of 10^{51} erg into acceleration of particles are assumed. The energy-dependent diffusion coefficient $D(E) = D_{10} \cdot (D/10\,\mathrm{GeV})^s$ cm^{2}s^{-1} is considered to have an exponent s of 0.5.

These assumptions allow us to calculate the expected γ-ray flux above 1 TeV from the molecular cloud dependent on the distance $D_{\rm SNR\text{-}MC}$ between the molecular cloud and the supernova remnant and on the normalization of the diffusion coefficient D_{10} at 10 GeV. The model of Gabici et al. [19] is used for this calculation. To obtain the explorable parameter space of the diffusion coefficient the

[1] Here: 1 C.U. $= I_{\rm Crab}(>1\,\mathrm{TeV}) = 2.26 \times 10^{-11}$ cm^{-2} s^{-1}.

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