Acceleration of cosmic rays and gamma-ray emission from supernova remnants in the Galaxy

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Accepted 2013 June 15. Received 2013 May 31; in original form 2013 February 7

ABSTRACT
Galactic cosmic rays are believed to be accelerated at supernova remnant shocks. Though very popular and robust, this conjecture still needs a conclusive proof. The strongest support to this idea is probably the fact that supernova remnants are observed in gamma-rays, which are indeed expected as the result of the hadronic interactions between the cosmic rays accelerated at the shock and the ambient gas. However, also leptonic processes can, in most cases, explain the observed gamma-ray emission. This implies that the detections in gamma-rays do not necessarily mean that supernova remnants accelerate cosmic ray protons. To overcome this degeneracy, the multiwavelength emission (from radio to gamma-rays) from individual supernova remnants has been studied and in a few cases it has been possible to ascribe the gamma-ray emission to one of the two processes (hadronic or leptonic). Here, we adopt a different approach and, instead of a case-by-case study we aim for a population study and we compute the number of supernova remnants which are expected to be seen in TeV gamma-rays above a given flux under the assumption that these objects indeed are the sources of cosmic rays. The predictions found here match well with current observational results, thus providing a novel consistency check for the supernova remnant paradigm for the origin of Galactic cosmic rays. Moreover, hints are presented for the fact that particle spectra significantly steeper than $E^{-2}$ are produced at supernova remnants. Finally, we expect that several of the supernova remnants detected by HESS in the survey of the Galactic plane should exhibit a gamma-ray emission dominated by hadronic processes (i.e. neutral-pion decay). The fraction of the detected remnants for which the leptonic emission dominates over the hadronic one depends on the assumed values of the physical parameters (especially the magnetic field strength at the shock) and can be as high as roughly a half.

Key words: cosmic rays – ISM: supernova remnants.

1 INTRODUCTION

Though cosmic rays (CRs) were discovered about a century ago (De Angelis 2012), the question about their origin is still a matter of discussion (see e.g. Drury et al. 2001; Aharonian et al. 2012, for reviews). Baade & Zwicky (1934) were the first to propose that supernovae are the sources of CRs, and this still remains the most popular scenario to explain the origin of Galactic CRs. The particle energy that marks the transition between Galactic and extragalactic CRs is believed to be located between the knee and the ankle and the particle energies that are observed in the CR spectrum at particle energies of a few PeV and a few $10^{18}$ eV, respectively (Blümer, Engel & Hörandel 2009). Thus, the acceleration mechanism connected to supernovae must be able to accelerate particles up to the PeV energy range and above. The present formulation of this idea is often referred to as the supernova remnant (SNR) paradigm for the origin of CRs, because the bulk of Galactic CRs are believed to be accelerated via first-order Fermi mechanism operating at SNR shocks (e.g. Hillas 2005; Helder et al. 2012).

The success of this paradigm relies on several facts. First of all, SNRs can provide the power needed to sustain the CR flux at the observed level, if some fraction (about 10–30 per cent) of their kinetic energy is somehow converted into relativistic particles (e.g. Ptuskin, Zirakashvili & Seo 2010, and references therein). Secondly, diffusive shock acceleration can operate at SNR shocks (for...
a review see Drury 1983), and this provides a viable mechanism to accelerate CRs. Diffusive shock acceleration is expected to accelerate particles with power-law spectra whose slope, once the effects of CR propagation in the Galaxy are taken into account, roughly matches the one of the CR spectrum as it is observed at the Earth (e.g. Ptuskin et al. 2010; Bell, Schure & Reville 2011; Caprioli 2012). Finally, during the acceleration process CRs can amplify the magnetic field at shocks via various plasma instabilities (e.g. Bell 1978, 2004; Drury & Downes 2012). Observations of SNRs in the X-ray domain strongly support this scenario (see Vink 2012, for a review) and indicate that the magnetic field strength at SNR shocks can grow up to several hundreds of microgauss, which is the value required to accelerate particles up to the knee. All these things support the idea that SNRs indeed are the sources of CRs, but it has to be kept in mind that an unambiguous and conclusive proof of such a statement is still missing.

The acceleration of CRs must be accompanied by the production of gamma-rays. This radiation is the result of the decay of neutral pions generated in hadronic interactions between the CRs and the ambient gas (Stecker 1971; Aharonian 2004). It was shown by Drury, Aharonian & Völk (1994) and Naito & Takahara (1994) that if SNRs indeed are the sources of CRs, then their gamma-ray emission must be strong enough to be detected by Cherenkov telescopes of the current generation. The detection of several SNRs in TeV gamma-rays nicely fits with these earlier predictions, but it cannot be considered a proof of the fact that SNRs can accelerate CRs. This is because electrons can also be accelerated at shocks, and their inverse Compton emission can also account for the observed TeV radiation (e.g. Aharonian et al. 2008a; Gabici 2008; Hinton & Hofmann 2009). The ambiguity between the hadronic or leptonic origin of the gamma-ray emission observed from SNRs is the main obstacle in proving (or falsifying) the SNR paradigm for the origin of CRs.

Very recently, the Fermi Collaboration reported on the detection of the characteristic pion-decay feature in the gamma-ray spectrum of two SNRs: IC 443 and W44. Such feature consists of a very steep rise of the spectral energy distribution below \( \approx 200\) MeV followed, at higher energies, by a broad energy spectrum that roughly mimics the energy distribution of the CR protons responsible for the emission. The steep rise is a unique signature of neutral-pion decay that cannot be reproduced by leptonic radiation mechanisms. For this reason, the observations by Fermi prove that CR protons are now being accelerated in the SNRs IC 443 and W44 (Ackermann et al. 2013).

Except for the two cases mentioned above, the attempts to distinguish between hadronic and leptonic origin of the gamma-ray emission are based on multiwavelength observations of SNRs, from the radio band to the very high energy gamma-ray domain. This is generally done on a case by case basis, i.e. multiwavelength data are collected for a specific SNR, and hadronic and/or leptonic models are fitted to data (see e.g. Morlino, Amato & Blasi 2009; Berezhko & Völk 2010; Zirakashvili & Aharonian 2010; Ellison et al. 2012, and references therein). In some cases, it has been possible to ascribe quite confidently the gamma-ray emission either to a hadronic or to a leptonic mechanism (Ellison et al. 2010; Abdo et al. 2011; Acciari et al. 2011; Morlino & Caprioli 2012), while for other cases the situation still remains ambiguous.

In this paper, we follow a different approach and, instead of considering one specific object, we investigate the gamma-ray properties of SNRs as a class of objects. We start from the assumption that SNRs are the sources of CRs. This assumption, together with the knowledge of the supernova rate in the Galaxy, allows us to infer the typical CR acceleration efficiency per SNR. Then, by means of a Monte Carlo method we simulate the location and time of explosion of all the supernovae in the Galaxy. Finally, from the information on the gas density, taken from Galactic surveys of CO and H I lines (that trace molecular and atomic hydrogen, respectively), it is possible to estimate the hadronic gamma-ray emission from each simulated SNR. A leptonic contribution is added, by treating the electron-to-proton ratio \( K_{\text{ep}} \) as a free parameter of the model. Following this procedure, it is possible to build mock catalogues of TeV-bright SNRs that can then be compared with the data coming, for example, from the HESS survey of the Galactic plane (Aharonian et al. 2005). Our results show that expectations match quite well current observations, providing an additional and novel consistency check for the SNR paradigm for the origin of Galactic CRs.

The paper is structured as follows: in Section 2, we describe a procedure to estimate the gamma-ray emission from an individual SNR at a given stage of evolution, while in Section 3 a Monte Carlo approach is adopted to simulate the position and time of explosion of all the supernovae that exploded in the Galaxy. These results are then used in Section 3 to estimate the number of SNR detectable in the Galaxy at a given gamma-ray flux. In Section 4, a comparison with existing data (mainly from the survey of the Galactic plane performed by the HESS Collaboration) is performed. Finally, we discuss the results and conclude in Sections 5 and 6, respectively.

2 A MODEL FOR CR ACCELERATION AND GAMMA-RAY PRODUCTION IN SNRS

In this section, we develop a model that couples the dynamical evolution of an SNR with the particle acceleration operating at the shock. The aim of the model is to obtain predictions for the gamma-ray emission from individual SNRs.

2.1 Dynamical evolution of SNRs

In order to determine the time evolution of the SNR shock radius and velocity, we follow the approach outlined in Ptuskin & Zirakashvili (2003, 2005), where a significant contribution of CRs to the pressure behind the SNR shock has been assumed.

Let us consider first the case of a thermonuclear, Type Ia supernova. The time evolution of the shock radius \( R_{\text{sh}} \) and velocity \( u_{\text{sh}} \) in the ejecta-dominated phase are described by the following self-similar expressions (Chevalier 1982; Ptuskin & Zirakashvili 2005):

\[
R_{\text{sh}} = 5.3 \left( \frac{\mathcal{E}_{51}}{n_0 M_{\odot}/\text{cm}^3} \right)^{1/7} t_{\text{kyr}}^{4/7} \text{ pc}
\]

\[
u_{\text{sh}} = 3.0 \times 10^3 \left( \frac{\mathcal{E}_{51}}{n_0 M_{\odot}/\text{cm}^3} \right)^{1/7} t_{\text{kyr}}^{-3/7} \text{ km s}^{-1},
\]

where \( \mathcal{E}_{51} \) is the supernova explosion energy unit of \( 10^{51} \) erg, \( n_0 \) is the ambient gas number density in \( \text{cm}^{-3} \), \( M_{\odot} \) is the mass ejected in the explosion in solar mass units, and \( t_{\text{kyr}} \) is the time after explosion expressed in kiloyears. To describe the SNR evolution during the adiabatic phase it is convenient to use the expressions

\[
\mathcal{E}_{51} = \frac{u_{\text{sh}}^2}{2} R_{\text{sh}} = \frac{u_{\text{sh}}^2}{2} (5.3 \left( \frac{\mathcal{E}_{51}}{n_0 M_{\odot}/\text{cm}^3} \right)^{1/7} t_{\text{kyr}}^{4/7})^2.
\]
\begin{equation}
R_{sh} = 4.3 \left( \frac{E_{51}}{n_0} \right)^{1/5} t_{5yr}^{2/5} \left( 1 - \frac{0.06 M_{5/6}^3}{E_{51}^{1/2} n_0^{1/2} t_{5yr}} \right)^{2/5} \text{pc}
\end{equation}

\begin{equation}
u_{sh} = 1.7 \times 10^3 \left( \frac{E_{51}}{n_0} \right)^{1/5} t_{5yr}^{-3/5} \left( 1 - \frac{0.06 M_{5/6}^3}{E_{51}^{1/2} n_0^{1/2} t_{5yr}} \right)^{-3/5} \text{km s}^{-1}
\end{equation}

which connect smoothly with equations (1) at a time $t_0 \approx 26000 M_{5}^{-3/2} E_{51}^{1/2} n_0^{-1/2}$ yr, and tend to the exact Sedov–Taylor solution (Sedov 1959; Taylor 1950) for $t \gg t_0$. We follow the SNR evolution until the time $t_{rad} \approx 3.6 \times 10^2 E_{51}^{1/4} n_0^{-1/4}$ yr, which marks the transition to the radiative phase (Cioffi, McKee & Bertshinger 1988).

Different expressions need to be adopted to describe the evolution of a core-collapse supernova, whose shock propagates in the wind-blown bubble generated by the wind of the progenitor star. Following Ptuskin & Zirakashvili (2005), we divide the wind-blown bubble into two regions: a dense red supersonic wind and a tenuous hot bubble which has been inflated by the wind of the massive progenitor star in main sequence. The red supersonic wind is assumed to be spherically symmetric with velocity $u_{w} = 10^6 u_{w,6}$ cm s$^{-1}$, mass-loss rate $M = 10^{-3} M_{\odot} \text{ yr}^{-1}$ and density $n_p = M/4\pi r_u u_{w} r^2$, where $r_u$ is the proton mass and $v_{th} \approx \mu m_p$ is the mean interstellar atom mass (here we adopt $\mu = 1.4$) and $r$ is the distance from the star. The radius of the wind is fixed to $R_{w} \approx 2$ pc, since its exact location does not affect significantly the results. The radius of the hot bubble is $R_{sh} = 28 (L^{1/6}/\mu n_0)^{1/5} t_{5yr}^{1/5}$ pc, where $L_{6}$ is the main-sequence star wind power in units of $10^{36}$ erg s$^{-1}$ and $t_{5yr}$ is the wind lifetime in units of megayears. The density inside the bubble is $n_p = 0.01 (L_{6}^{1/6}/\mu n_0^{1/2} M_{5}^{1/2})^{1/5}$ cm$^{-3}$ (Weaver et al. 1977). Here, we assume $t_{5yr}$ to be of the order of several Myr, which corresponds to the duration of the main-sequence phase of very massive stars (Longair 2011).

One might argue that, in fact, massive stars generally form in clusters or associations. In this case, it is the collective effect of several stellar winds that creates a cavity in the surrounding medium. The size of this cavity is quite large $R_{sh} = 270 (L_{6}^{1/6}/\mu n_0)^{1/5} t_{10 Myr}^{1/5}$ pc (Mac Low & McCray 1988), where $L_{6}^{1/5}$ is the total mechanical power provided by stellar winds and supernovae inside the bubble in units of $10^{36}$ erg s$^{-1}$ and $t_{10 Myr}$ is the time in units of $10^7$ yr since the formation of the star cluster. The average density into the cavity is $n_p \approx 0.01 (L_{6}^{1/6}/\mu n_0^{1/2} M_{5}^{1/2})^{1/5} v_{th}^{-1}$ cm$^{-3}$ (Parizot et al. 2004). Since this density is quite close to the one obtained above for a bubble inflated by a single star in the interstellar medium, we conclude that the evolution of a given SNR is similar in the two scenarios. In such a structured interstellar medium, the evolution of the SNR shock during the ejecta-dominated phase is described by (Chevalier 1982; Ptuskin & Zirakashvili 2005):

\begin{equation}
R_{sh} = 7.7 \left( \frac{E_{51}^{1/2} u_{w,6}}{M_{\odot} M_{5}^{1/2}} \right)^{1/8} t_{5yr}^{7/8} \text{pc}
\end{equation}

\begin{equation}
u_{sh} = 6.6 \times 10^3 \left( \frac{E_{51}^{1/2} u_{w,6}}{M_{\odot} M_{5}^{1/2}} \right)^{1/8} t_{5yr}^{1/8} \text{km s}^{-1}
\end{equation}

Fairly accurate expressions that describe the evolution of an SNR in the adiabatic phase can be obtained, in this case, by adopting the thin-shell approximation (e.g. Bisnovatyi-Kogan & Silich 1995; Ostriker & McKee 1995), i.e. the assumption that the gas swept up by the SNR shock is concentrated in a thin layer behind the shock front. The following equations can be derived, where the shock speed and SNR age are parametrized as functions of the shock radius (Ptuskin & Zirakashvili 2005):

\begin{equation}
u_{sh}(R_{sh}) = \frac{\gamma_{ad} + 1}{2} \left( \frac{12(\gamma_{ad} - 1)\mathcal{E}}{(\gamma_{ad} - 1)M^2(R_{sh})^3} \times \int_0^{R_{sh}} dr r^{6(\gamma_{ad} - 1)/3(\gamma_{ad} + 1) - 1} M(r) \right)^{1/2}
\end{equation}

where $\mathcal{E}$ is the energy provided by stellar winds and supernovae inside the bubble and $M(R_{sh})$ is the total gas mass inside the SNR shock (ejecta-swept-up). Equations (3) and (4) are fitted together at the transition between the ejecta-dominated and adiabatic phases. We follow the evolution of the SNR until the Mach number drops to $\approx 3$, or, if shorter, until the time at which the SNR shock impacts on to the unperturbed (and much denser than the gas inside the bubble) interstellar medium and becomes quickly radiative.

The internal structure of the SNR is determined by adopting the linear velocity approximation (Ostriker & McKee 1995), in which the gas velocity profile for $r < R_{sh}$ is given by

\begin{equation}
u(r, t) = \left( 1 - \frac{r}{R_{sh}(t)} \right) \frac{u_{sh}(t)}{R_{sh}(t)}
\end{equation}

In the expressions above, $\gamma_{ad}$ is the gas adiabatic index and $M(R_{sh})$ is the total gas mass inside the SNR shock (ejecta-swept-up). Equations (3) and (4) are fitted together at the transition between the ejecta-dominated and adiabatic phases. We follow the evolution of the SNR until the Mach number drops to $\approx 3$, or, if shorter, until the time at which the SNR shock impacts on to the unperturbed (and much denser than the gas inside the bubble) interstellar medium and becomes quickly radiative.

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The goal of this section is to obtain an estimate of the gamma-ray emission from a given SNR shell. Both the nuclei and the electrons which are accelerated at the SNR shock contribute to the emission through neutral-pion decay and inverse Compton processes, respectively. The radiation produced by escaping CRs in the vicinity of the SNR is not considered here.

Let $f(r, p, t)$ be the CR particle distribution function at a given time $t$ after the supernova explosion and at a given position $r < R_{sh}$ inside the SNR. Here, $p$ is the particle momentum. We assume that particles are accelerated at the shock with a power-law spectrum so that $f_0(p, t) \equiv f(R_{sh}, p, t) = A(t) p^{-\alpha}$, where $\alpha$ is treated as a free parameter with values in the range $\alpha > 4$ (see e.g. Zirakashvili & Ptuskin 2008b; Caprioli 2012). Values significantly larger than $\alpha = 4$ are needed to reproduce the slope of the CR spectrum observed at the Earth. This requirement comes from theoretical studies of particle escape...
from SNRs (e.g. Ptuskin & Zirakashvili 2005; Caprioli, Amato & Blasi 2010; Ohira, Murase & Yamazaki 2010; Gabrić 2011) coupled with studies of the propagation of CRs in the Galaxy (see e.g. Strong, Moskalenko & Ptuskin 2007, and references therein). In the following, we will consider two representative cases: $\alpha = 4.4$ (soft spectrum) and $\alpha = 4.1$ (hard spectrum). The normalization $A$ of the CR spectrum is computed by assuming that the CR pressure at the shock is equal to some fraction $\xi_{CR}$ of the shock ram pressure:

$$P_{CR} = \xi_{CR} E_{up} u_{sh}$$

with $E_{up}$ representing the gas mass density upstream of the shock. The parameter $\xi_{CR}$ is a way to express the acceleration efficiency at the shock. For spectra steeper than $\alpha = 4$, the dominant contribution to the CR pressure comes from particles with momentum $p \approx m_{p} c$. On the other hand, the maximum momentum $p_{\text{max}}$ of the accelerated particles is determined here by the equality:

$$I_d = \frac{D(p_{\text{max}})}{u_{sh}} \approx \zeta R_{sh}$$

where $D$ represents the momentum-dependent diffusion coefficient for CRs upstream of the shock. In this way, $p_{\text{max}}$ is defined as the momentum for which the diffusion length of particles ahead of the shock $I_d$ equates to some fraction $\zeta$ of the shock radius. Particles with larger momentum are characterized by larger diffusion length and are assumed to escape the SNR. Studies of particle acceleration and escape from shocks suggest that $\zeta \approx 0.05-0.1$ (e.g. Zirakashvili & Ptuskin 2008a, and references therein). In the following, we will adopt the value $\zeta = 0.1$.

The particle diffusion coefficient at the shock depends on the magnetic field strength and on its turbulent structure. If the CR acceleration efficiency is high, the intensity of the turbulent magnetic field at shocks is expected to be strongly amplified with respect to the typical value found in the interstellar medium, and the diffusion coefficient is suppressed accordingly. The field amplification might be due to a CR current-driven instability (Bell 2004) or to resonant streaming instability (Lagage & Cesarsky 1983). The determination of the CR diffusion coefficient in the turbulent magnetic field at shocks is still an open issue. Here, we make the assumption that, in the presence of efficient field amplification, the CR diffusion coefficient is of the Bohm type in the amplified field. The expression for the Bohm diffusion coefficient is $D = R_{L} c / 3$ and $R_{L} = p c / q B$ is the particle Larmor radius. In the expressions above, $c$ is the speed of light, $q$ the elementary charge, and $B$ the amplified magnetic field. To estimate the value of the amplified field, we rely on the interpretation of X-ray data from SNRs made by Völk, Berezhko & Ksenofontov (2005). Starting from the observations of X-ray filaments in several young SNRs, they estimated the magnetic field intensity just downstream of the shock wave. They found that a fraction $\xi_B \approx 3.5$ per cent of the shock ram pressure $E_{up} u_{sh}^2$ is, on average, converted into magnetic field. By assuming that this fraction remains constant during the SNR lifetime, an expression for the amplified magnetic field strength immediately downstream of the shock can be derived, and reads

$$B_{\text{down}} = B_0 \sigma \left( \frac{u_{sh}}{v_d} \right)^2 + 1,$$

where $B_0 \approx 5 \mu G$ is the magnetic field in the interstellar medium and $v_d$ is a velocity that defines the importance of wave damping in limiting the field amplification (e.g. Caprioli et al. 2010). In equation (8), the term under the square root represents the amplification due to the CR instability operating upstream of the shock, while the factor $\sigma$ mimics the effect of the field compression at the shock.

For shock velocities larger than $v_d$, the damping of the magnetic turbulence at the shock is negligible, and thus the field can be effectively amplified. On the other hand, damping dominates for smaller velocities. Following Zirakashvili & Aharonian (2010), we adopt the following expression for $v_d$:

$$v_d = \left( \frac{\sigma^2 B_0^2}{8 \pi \xi_B E_{up}} \right)^{1/2} \approx 2 \times 10^7 n_0^{-1/2} \text{ cm s}^{-1},$$

which is in substantial agreement with the results of more sophisticated studies (e.g. Ptuskin & Zirakashvili 2003). Moreover, we adopt here a diffusion coefficient for CRs at the shock of the form (Zirakashvili & Ptuskin 2012):

$$D = D_0 \left( 1 + \frac{v_d^2}{u_{sh}^2} \right)^g,$$

where $D_0$ is the Bohm diffusion coefficient and the parameter $g$ depends on the nature of the dominant damping mechanism. We fix here $g = 3$, as appropriate for a Kolmogorov type of non-linear damping (Ptuskin & Zirakashvili 2003). Equation (10) is valid in both regimes $u_{sh} > v_d$ and $u_{sh} < v_d$; in the former, the diffusion coefficient coincides with the Bohm one, while in the latter it is significantly larger, due to wave damping.

It is evident from equation (8) that the amplified field, being proportional to the shock speed, decreases with time, as long as $u_{sh} \gg v_d$.

$$B_{\text{down}} \approx 140 \left( \frac{u_{sh}}{1000 \text{ km s}^{-1}} \right) n_0^{1/2} \mu G.$$

After that, field amplification becomes inefficient and the magnetic field downstream of the shock stays constant in time and is equal to $\alpha B_0$ (i.e. only the compression of the field at the shock is taken into account). This fact, once combined with equation (7), implies that the maximum momentum of the protons that can be confined and accelerated at the shock decreases with time. As an illustrative example, for an SNR expanding adiabatically in an uniform medium equations (8) and (11) give, for $u_{sh} \gg v_d$, $B \propto u_{sh} \propto r^{-3/5}$, which corresponds to (equation 7) $p_{\text{max}} \propto r^{-3/5}$. A quantitative expression for the maximum energy $E_{\text{max}} = p_{\text{max}} c$ can easily be computed and reads

$$E_{\text{max}} \approx 280 E_{51}^{3/5} n_0^{-1/10} \frac{4}{30} \text{ TeV},$$

which implies that at an age of few hundred years SNRs are capable of accelerating particles up to the PeV domain. In the opposite situation in which the magnetic field at the shock is not amplified and stays constant in time, the maximum momentum of protons exhibits a very slow decline in time. This happens at late times and can be described as

$$E_{\text{max}} \approx 17 \left( \frac{E_{51}}{n_0} \right)^{2/5} \left( \frac{n_{\text{HI}}}{30} \right)^{-1/5} \times \left[ 1 + 0.1 \left( \frac{n_{\text{HI}}}{30 n_0 E_{51}} \right)^{3/5} \right]^{-3} \text{ TeV}.$$

Similar estimates can be obtained also for supernovae exploding in a structured medium (i.e. wind plus bubble), though analytic expressions cannot be written in this case.

The spatial distribution of CRs inside the remnant can be computed by solving the transport equation:

$$\frac{\partial f}{\partial t} + u \nabla f - \nabla DF f - \frac{p}{\rho} \nabla u \frac{\partial f}{\partial p} = 0.$$
where $D$ is a momentum dependent diffusion coefficient for CRs. Particles with momenta smaller than $p_{\text{max}}$ are expected to be well confined within the SNR. Thus, equation (14) can be solved by dropping the diffusion term $V D V f$, which is expected to be negligible when compared to the advection term $u V f$. The solution of this differential equation can be found by using the method of the characteristics and adopting the boundary condition $f(R, p, t) = f_0(p, t)$.

The acceleration of electrons at shocks proceeds at the same rate as for protons, but their spectrum is different because electrons suffer synchrotron and inverse Compton losses, while protons are virtually loss-free. At low energies, where energy losses can be neglected, the acceleration of electrons and protons at the shock proceeds in an identical manner, implying that the same spectral shape is expected for both species. Thus, it is possible to introduce a parameter $K_{ep}$, generally believed to be much smaller than unity, that describes the ratio between the electron and proton spectra at low energies. Values of $K_{ep}$ in the range $\approx 10^{-3} - 10^{-2}$ are obtained from spectral fits to the multiwavelength emission from individual SNRs (e.g. Ellison et al. 2010; Berezhko, Ksenofontov & Völk 2012; Morlino & Caprioli 2012). As it will be shown in the following, for smaller values of $K_{ep}$ (of the order of $\approx 10^{-5}$ or less) the gamma-ray emission from electrons becomes totally negligible. For this reason, we consider in the following the range $10^{-5} < K_{ep} < 10^{-2}$.

The maximum energy of the electrons accelerated at a shock can be obtained by equating the acceleration rate at the shock to the synchrotron energy loss time. To compute this, we follow the approach described in Vannoni, Gabici & Aharonian (2009), which gives

$$E_{\text{max}}^e \approx 7.3 \left(\frac{u_{\text{sh}}}{100 \, \text{km} \, \text{s}^{-1}}\right) \left(\frac{B_{\text{down}}}{100 \, \mu\text{G}}\right)^{-1/2} \text{TeV}. \quad (15)$$

At this energy, a cutoff appears in the electron spectrum, with shape $\propto \exp[-(E/E_{\text{max}}^e)^2]$ (Zirakashvili & Aharonian 2007).

Electrons are accelerated very quickly, over time-scales significantly shorter than the synchrotron energy loss time which, for 10 TeV electrons in a 100 $\mu$G field is of the order of a century. After being accelerated they are advected downstream of the shock, where they continue to lose energy mainly through synchrotron radiation, with a characteristic time:

$$\tau_{\text{syn}} \approx 1.8 \times 10^3 \left(\frac{E}{\text{TeV}}\right)^{-1} \left(\frac{B_{\text{down}}}{100 \, \mu\text{G}}\right)^{-2} \text{yr}. \quad (16)$$

where $E_e$ is the electron energy. The energy loss time decreases with particle energy and this implies that an energy $E_{\text{break}}^e$ exists above which the loss time is shorter than the SNR age $\tau_{\text{age}}$. Above such energy, the electron spectrum is shaped by radiative losses and steepens by one power in momentum (see e.g. Morlino & Caprioli 2012). In fact, since the SNR is expanding also adiabatic losses have to be taken into account, with a rate $\tau_{\text{ad}} = R_{\text{sh}}/u_{\text{sh}}$. After a comparison with the work of Finke & Dermer (2012), we found that an appropriate expression for $E_{\text{break}}^e$ can be found by solving the equation $\tau_{\text{age}}^{-1} = \tau_{\text{syn}}^{-1} + \tau_{\text{ad}}^{-1}$.

Two things have to be noted. First, if the magnetic field is not strong enough, $E_{\text{break}}^e$ can easily become larger than $E_{\text{max}}^e$. In this case, no break appears and the electron spectrum has the same shape as the one of protons up to $E_{\text{max}}^e$. Secondly, in some situations equation (7) can be more stringent than equation (15) (i.e. the acceleration of electrons is limited by escape rather that by energy losses), and in this case the former is used to estimate the energy of the cutoff in the electron spectrum.

The last missing piece of information is the value of the parameter $\xi_{\text{CR}}$, defined in equation (6), which represents the particle acceleration efficiency at the shock. In order to estimate this parameter, we assume that SNRs are the sources of Galactic CRs. The estimated CR luminosity of the Galaxy is of the order of $L_{\text{MW}}^\text{CR} \approx 10^{41} \text{erg s}^{-1}$ and this number is quite stable with respect to the assumptions made to derive it (Dogiel, Shönfelder & Strong 2002; Strong et al. 2010). By combining this information with the estimated rate of supernovae in the Galaxy $\nu_{\text{SN}} \approx 3 \text{ per century}$ (e.g. Li et al. 2011, and references therein) it is possible to obtain the average fraction of the supernova explosion energy that needs to be converted into CRs in order to provide the required power $L_{\text{MW}}^\text{CR}$. This gives

$$\eta_{\text{CR}} = \frac{L_{\text{MW}}^\text{CR} \nu_{\text{SN}}}{E_{\text{SN}}} \approx 0.1 \left(\frac{L_{\text{MW}}^\text{CR}}{10^{41} \text{erg s}^{-1}}\right) \left(\frac{\nu_{\text{SN}}}{0.03 \text{ yr}^{-1}}\right) \left(\frac{E_{\text{SN}}}{10^{51} \text{erg}}\right)^{-1}. \quad (17)$$

The parameter $\eta_{\text{CR}}$ represents the global (i.e. integrated over the whole SNR lifetime) CR output from a single SNR, while the parameter $\xi_{\text{CR}}$ that appears in equation (6) measures the instantaneous (i.e. at a specific time) acceleration efficiency at the shock. Following the results presented by Zirakashvili & Ptuskin (2012) and Caprioli (2012), we will assume in the following that $\xi_{\text{CR}}$ remains constant over the SNR lifetime up to the end of the Sedov phase and that $\xi_{\text{CR}} \approx \eta_{\text{CR}} \approx 0.1$. However, the value of the CR acceleration efficiency which is expected from theoretical studies of non-linear shock acceleration is generally significantly larger than the modest $\eta_{\text{CR}} \approx 0.1$ per cent needed to sustain the observed flux of Galactic CRs. One way to solve this apparent discrepancy is to assume that CRs can be accelerated with high efficiency (and thus modify the shock structure) only in a small fraction of the shock surface (see e.g. Völk, Berezhko & Ksenofontov 2003; Berezhko, Ksenofontov & Völk 2009; Zirakashvili & Ptuskin 2012). Thus, here the value $\xi_{\text{CR}} \approx 0.1$ has to be considered as an average over the whole SNR shock surface.

The procedure described in this section allows us to determine the spectrum and the spatial distribution of CRs inside an SNR. By combining these results with the spatial distribution of the gas inside the SNR as obtained in Section 2.1, the gamma-ray luminosity from a given SNR can be computed, by adding the hadronic contribution from proton–proton interactions (Kelner, Aharonian & Bugayov 2006) to the leptonic one from inverse Compton scattering off photons in the cosmic microwave background (Blumenthal & Gould 1977). While computing the gamma-ray emission from proton–proton interactions, the results from Kelner et al. (2006) have been multiplied by a factor of $\approx 1.8$ to take into account the presence of nuclei heavier than hydrogen in both ambient gas and CRs (Mori 2009).

3 ON THE NUMBER OF SNRS DETECTABLE IN THE TEV ENERGY DOMAIN: A MONTE CARLO APPROACH

In this section, we describe the simulation procedure adopted to predict the number of Galactic SNRs with a given gamma-ray flux. Since this work is focused on the TeV energy domain, in the following we will always consider integral fluxes computed above a
A Monte Carlo approach is used to simulate the time of explosion of all the supernovae in the Galaxy (i.e. the age of all the SNRs in the Galaxy). This has been done by assuming a supernova explosion rate constant in time and equal to \( v_{SN} = 3 \) per century (Li et al. 2011). This implies an acceleration efficiency at the shock of the order of \( \eta_{CR} \approx 10 \) per cent (see equation 17). Different values of \( v_{SN} \) will be also discussed in the following. Once the age of an SNR is known, its location within the Galaxy is determined by following the prescription described in Faucher-Giguère & Kaspi (2006). This consists in assuming that the radial distribution of SNRs in the Galaxy follows the distribution of pulsars, as determined by Yusifov & Küçük (2004) and Lorimer (2004). In addition to that, four spiral arms are considered, each arm following a logarithmic spiral shape (see table 2 in Faucher-Giguère & Kaspi 2006). The width of the arms has been modelled as in Blasi & Amato (2012). To determine the height above (or below) the Galactic plane of an SNR, we assume that the vertical distribution of supernovae follows the one of the gas. We use the vertical distribution of molecular and atomic hydrogen for core-collapse and Type Ia supernovae, respectively (Shibata, Ishikawa & Sekiguchi 2011), which implies that the distribution of Type Ia supernovae has a height above the disc which is significantly larger than the one of core-collapse supernovae. In the absence of a detailed knowledge of the spatial distribution of supernovae of a given type, this assumption mimics the fact that core-collapse supernovae are expected to explode in dense star-forming regions, while thermonuclear ones can be found also in low-density regions.

The dynamical evolution of each simulated SNR is then determined as explained in Section 2.1. The evolution depends mainly on the value of the ambient density at the location of the SNR and on the supernova type. To determine the value of the ambient density, we use the three-dimensional distributions (Galactic latitude, longitude and radial velocity) of atomic (H\(i\)) and molecular (H\(2\)) hydrogen given by Nakanishi & Sofue (2003, 2006). The three-dimensional spatial distribution of the gas (i.e. the conversion from radial velocity to distance) is computed as in Casanova et al. (2010). The spatial resolution of the distribution of gas obtained in this way is of the order of \( \approx 50-100 \) pc, which is appropriate to describe the large-scale structure of the interstellar medium, but too coarse to describe small-scale structures such as molecular clouds. The possible effects of the poor spatial resolution on our results will be discussed in Section 5. Four types of supernovae are considered: Ia, IIP, Ib/c and IIb, with relative rates 0.32, 0.44, 0.22 and 0.02, respectively (Puskin et al. 2010). The parameters used for each supernova type to compute the SNR dynamical evolution are listed in Table 1. The gamma-ray emission from each SNR is then computed as described in Section 2.2.

### Table 1. Supernova parameters adopted in the simulation: supernova type (column 1), explosion energy in units of \( 10^{51} \) erg (column 2), mass of ejecta in solar masses (column 3), the wind mass-loss rate in \( M_\odot \) yr\(^{-1} \) (column 4), the wind speed in units of \( 10 \) km s\(^{-1} \) (column 5) and the relative explosion rate (column 6). Values from Puskin et al. (2010).

| Type  | \( E_{51} \) | \( M_{\odot, ej} \) | \( M_\odot \) | \( u_{e,6} \) | Rel. rate |
|-------|-------------|--------------------|---------------|-------------|---------|
| Ia    | 1           | 1.4                | –             | 0.32        |         |
| IIP   | 1           | 8                  | 1             | 1           | 0.44    |
| Ib/c  | 1           | 2                  | 1             | 1           | 0.22    |
| IIb   | 3           | 1                  | 10            | 1           | 0.02    |

The procedure described in this section can be used to simulate the number of SNRs that one can expect to detect with a Cherenkov telescope with a given sensitivity. This will be done in the next section, where the prediction from our Monte Carlo will be compared with the data from the survey of the Galactic plane performed by the HESS Collaboration. Before doing that, we compute here the total number of SNRs in the Galaxy which are expected to emit gamma-rays above a given flux. All the results reported in the following have been obtained by averaging 1000 Monte Carlo realizations of the Galaxy.

We first consider a situation in which the magnetic field at the shock is not amplified. In this case, particles are accelerated at a shock characterized by an upstream magnetic field of \( B_{up} = B_0 \approx 5 \) \( \mu \)G and a downstream magnetic field of \( B_{down} = \sigma B_0 \approx 30 \) \( \mu \)G. In Fig. 1 we plot the number of SNRs in the Galaxy which are expected to have an integral gamma-ray flux above a given value. Integral fluxes above 1 TeV are considered. The red solid line shows our prediction for a soft spectrum of accelerated CRs with slope \( \alpha = 4.4 \). A very small electron-to-proton ratio \( K_{ep} = 10^{-5} \) is assumed, and this insures that for all the SNRs the hadronic emission largely dominates over the leptonic one. To check this, we repeated the simulation for smaller values of \( K_{ep} \) and found no appreciable difference in the results, while for larger values of \( K_{ep} \) the results change significantly. In other words, when \( K_{ep} \) drops below \( 10^{-5} \) the contribution of electrons to the gamma-ray emission becomes totally negligible, and the exact value of the electron-to-proton ratio no longer plays a role. The shaded red region around the curve shows the fluctuations of the results due to the stochasticity of the process. To estimate that, histograms representing the number of realizations that correspond to a given number of detections were produced and fitted with continuous functions. The shaded region represents the interval within which 68.2 per cent of the area below the fitting function is contained. The black dashed curve (as well as the shaded black region) has been computed, instead, by assuming a high electron-to-proton ratio \( K_{ep} = 10^{-2} \). The number of SNRs expected at each flux is increased by a factor of \( \gtrsim 1.5 \) with respect to the case \( K_{ep} = 10^{-5} \), and this is due to the fact that the leptonic contribution is no longer negligible. The fact that the increase in the number of TeV-bright SNRs is modest but not negligible (it is indeed close to a factor of 2) indicates that for \( K_{ep} = 10^{-6} \) the number of SNRs for which the hadronic emission dominates the photon energy of 1 TeV. A discussion of the expected gamma-ray emission of SNRs in the GeV energy range is provided in Section 6.
gamma-ray flux is of the same order of the number of SNRs for which the leptonic emission dominates.

The number of SNRs with an integral flux greater than 1 per cent of the Crab ($\approx 2.3 \times 10^{-13} \text{ cm}^{-2} \text{ s}^{-1}$; Aharonian et al. 2006c), a representative flux sensitivity for deep pointed observations of point-like sources with Cherenkov telescopes of current generation, is $\approx 13$ and $21$ for the red and black curve, respectively (the effect of the source extension on to the telescope sensitivity is neglected here, and will be discussed in the next section). On the other hand, the probability of detecting very bright SNRs with fluxes of the order of $10^{-11} \text{ cm}^{-2} \text{ s}^{-1}$ is small, but not completely negligible. For this value of the integral flux, the mean values for the expected number of gamma-ray SNRs are $\approx 0.2$ and $\approx 0.5$ for the red and black curve, respectively, while the shaded regions (representing one standard deviation) extends up to $\approx 1.3$ and $\approx 1.7$. This is still consistent, though in some tension with the fact that two SNRs were detected at such flux levels: RX J1713.7−3946, with an integral flux equal to $F(>1 \text{ TeV}) \approx 1.6 \times 10^{-11} \text{ cm}^{-2} \text{ s}^{-1}$ (Aharonian et al. 2006b) and Vela Jr, with an integral flux equal to $F(>1 \text{ TeV}) \approx 1.5 \times 10^{-11} \text{ cm}^{-2} \text{ s}^{-1}$ (Aharonian et al. 2007). Unfortunately, a more quantitative comparison between our predictions and available data is, at this stage, not easy to be performed, due to the lack of a complete catalogue of TeV gamma-ray bright SNRs. This point will be extensively discussed in Section 4.

A much more plausible scenario, supported by both theory (Bell 2004) and observations (Vink 2012), is the one in which the magnetic field at the shock is substantially amplified due to CR-induced instabilities that may operate in the shock precursor. In this case, the values of the magnetic field and of the maximum energy of accelerated protons can reach values up to hundreds of microgauss and PeV energies or even more, respectively. These high values are achieved early in the evolution of the SNR and then gradually decrease with time as the shock slows down. A plausible parametrization of this behaviour has been described in Section 2.2. The expected number of SNRs with integral flux above $F(>1 \text{ TeV})$ is shown in Fig. 2 for $K_{ep} = 10^{-2}$ and $10^{-5}$ (red and black curve, respectively). The dashed regions have the same meaning as in Fig. 1. The number of SNRs with flux above the 1 per cent of the Crab is $\approx 32$ and $\approx 39$ for the red and black curve, respectively. The mean value for the number of very bright SNRs, with fluxes above $10^{-11} \text{ cm}^{-2} \text{ s}^{-1}$, is, for both curves, $\approx 1$, in closer agreement with the detection of the two very bright SNRs.

The first thing to be noted is that for $K_{ep} = 10^{-5}$ (i.e. no leptonic contribution to the gamma-ray emission) the number of SNRs at a given flux is larger (by roughly a factor of $\approx 2$—4) when the magnetic field is amplified. This can be seen by comparing the red lines in Figs 1 and 2. The reason for this is the fact that, in order to detect the hadronic interaction of an SNR above a photon energy of 1 TeV, the underlying proton spectrum must extend up to energies significantly larger than $\approx 10 \text{ TeV}$, because these are the particles that produce the photons with energy in excess of 1 TeV. The maximum energy of the protons accelerated at the shock is larger if the field is amplified and thus, in this case, SNRs remain visible above 1 TeV for a longer time. This explains why one expects to see more gamma-ray SNRs if the magnetic field is amplified (even if the acceleration efficiency is the same in the two cases).

Another thing to be noted is that, if the field is amplified, there is not much difference in our predictions if a low or a high value of the electron-to-proton ratio $K_{ep}$ is adopted. In fact, the black and red curves in Fig. 2, which refer to $K_{ep} = 10^{-2}$ and $10^{-5}$, are virtually identical for gamma-ray fluxes larger than $10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$, and remain comparable for all the values of the gamma-ray fluxes (the difference between the two curves is always less than $\approx 30$ per cent). This implies that the leptonic gamma-ray emission from SNRs never plays a crucial role. If the field is amplified, electrons suffer severe synchrotron energy losses, and as a consequence of that, their spectrum exhibit a break at an energy which can be computed by equating the energy loss time with the SNR age (see the discussion following equation 16). For large values of the field (few hundreds microgauss) and typical SNR ages of thousands of years, the break appears at TeV energies. The electron spectrum below the break is identical to the proton one (i.e. it is a power law in momentum with slope 4.4) while above the break the spectrum steepens by one power in momentum. Such steepening suppresses the leptonic emission in the TeV domain, and explains why the parameter $K_{ep}$ virtually plays no role in this case.

In computing the curves in Fig. 2, we assumed that the magnetic field downstream of the shock is the amplified one, as determined by equation (11). This might not be the case if the turbulent magnetic field is damped downstream of the shock (e.g. Pohl, Yan & Lazarian 2005). This fact led Atoyan & Dermer (2012) to build a two-zone model for SNRs in which particles are accelerated in a small region around the shock wave (zone 1), where the magnetic field is amplified. Particles are subsequently transported (through advection and diffusion) further inside the SNR (zone 2), where the magnetic field strength may be smaller. In the Atoyan & Dermer model, the acceleration region is much smaller than the inner region, and thus the electrons spend most of the time in the latter. Interestingly, this allowed them to decouple the region where electrons are accelerated (zone 1, where the magnetic field strength is large) from the one in which they suffer most of the synchrotron losses (zone 2, where the field strength is smaller). Assuming the existence of two zones with different magnetic field can significantly affect the predictions of the electron spectrum and that of the leptonic gamma-ray emission from SNRs. Here, we adopt the following simplified view: we neglect particle diffusion and we assume that electrons, after being accelerated in zone 1 are quickly advected into zone 2, which is characterized by a low field. In this case, the maximum energy of accelerated electrons is computed through equation (15), where $B_{down}$ is the amplified field, while in order to compute the energy of the break in the spectrum [see equation (16) and following discussion] we adopt a smaller value for the magnetic field. As an illustrative example, we adopt here a constant value of 30 $\mu$G for the field strength in the inner

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**Figure 2.** Same as in Fig. 1 with the only exception that an amplified field has been considered (models M3 and M4 in Table 2).
region (the effect of changing this field will be discussed in Section 5).

Results for this two-zone model are shown in Fig. 3. The black curve has been computed for a CR spectrum at injection with slope $\alpha = 4.4$ and for $K_{ep} = 10^{-2}$. The magnetic field at the shock is the amplified one (equation 11) while the field in zone 2 is 30 $\mu$G. Due to the lower value of the magnetic field in zone 2, synchrotron losses are less severe and the break in the electron spectrum moves upwards in energy, thus enhancing the Compton inverse radiation. This explains the larger number of gamma-ray bright SNRs expected in this case, when compared to the one-zone model illustrated in Fig. 2. The number of SNRs with integral gamma-ray flux above 1 percent of the Crab flux is $\approx 57$ while the mean value for the expected number of very bright SNRs with integral flux above $F(>1\ TeV) = 10^{-11}\ cm^{-2}\ s^{-1}$ is $\approx 1.6$.

Finally, the red curve in Fig. 3 shows the expectations for a hard spectrum of the accelerated CRs with $\alpha = 4.1$ (all the other parameters are left unchanged). The evident effect of an hard spectrum is a large increase of the number of gamma-ray SNRs. In this case, the expected number of SNRs with integral flux above 1 percent of the Crab is unreasonably large $\approx 190$, while the mean number of very bright SNRs with flux above $10^{-11}\ cm^{-2}\ s^{-1}$ is $\approx 8.1$, also exceedingly large. This clearly disfavours a scenario in which SNRs accelerate a hard spectrum of particles. Spectra significantly steeper than $\alpha = 4$ are needed to be consistent with observations, if a standard $\approx 10$ percent CR acceleration efficiency is assumed. This point will be further discussed in the next section.

Finally, it is instructive to estimate the total number of SNRs which are currently in the Sedov stage of their dynamical evolution. This would provide a strict (and clearly overoptimistic) upper limit for the number of possible detections in gamma-rays, since CR production is believed to be efficient only during this phase of the SNR evolution. By assuming a duration of the Sedov phase equal to a few $10^{5}$ yr and three supernovae explosions per century in the Galaxy, this number turns out to be $\approx 1000$. Thus, for the cases considered above, even for the most optimistic, the SNRs with TeV gamma-ray fluxes above the level of 1 percent of the Crab are a small fraction ($\approx 0.01$–0.1) of the total number of SNR which are believed to accelerate CRs in the Galaxy.

![Figure 3](https://www.mpi-hd.mpg.de/hfm/HESS/pages/home/sources/)

**Table 2. Values of the parameters adopted to compute the curves in Figs 1 (model M1 and M2), 2 (M3 and M4) and 3 (M5 and M6). $\alpha$ is the slope of the spectrum of CRs accelerated at the shock, and $K_{ep}$ is the electron-to-proton ratio. The last two columns specify whether or not magnetic field amplification has been taken into account, and the number of zones adopted to compute the inverse Compton radiation from electrons (see the text for more details).**

| Model | $\alpha$ | $K_{ep}$ | Amplified $B$ | Number of zones |
|-------|---------|---------|-------------|----------------|
| M1    | 4.4     | $10^{-5}$ | OFF         | 1              |
| M2    | 4.4     | $10^{-2}$ | OFF         | 1              |
| M3    | 4.4     | $10^{-5}$ | ON          | 1              |
| M4    | 4.4     | $10^{-2}$ | ON          | 1              |
| M5    | 4.4     | $10^{-2}$ | ON          | 2              |
| M6    | 4.1     | $10^{-2}$ | ON          | 2              |

For the reader’s convenience, the parameters which were used to compute the curves in Figs 1–3 are listed in Table 2.

**4 SNRS AND SKY SURVEYS IN THE TEV ENERGY DOMAIN**

In this section, we perform a comparison between the predictions described above and the data currently available in the TeV gamma-ray domain. With this respect, the data obtained by the HESS array of Cherenkov telescopes seem to be the most appropriate. Due to the large instrumental field of view (\(\approx 5\)°), it has been possible to obtain a deep scan of the Galactic plane at TeV energies by using only a relatively small fraction of the total available observing time. The results of this scan were published in a series of papers (Aharonian et al. 2005, 2006a; Gast et al. 2012). The aim of the scan is to obtain a good compromise between the fraction of the sky covered by the survey and the depth and spatial homogeneity of the exposure. The original HESS survey covered the range of $|l| < 30^\circ$ in Galactic longitude and $|b| < 3^\circ$ in latitude (Aharonian et al. 2005), and it has been gradually extended thereafter, especially in longitude. To date, an extension in the range of $l = 250^\circ–65^\circ$ was reported (Gast et al. 2012). However, from fig. 2 in that paper, it can be noticed that the exposure, and thus the sensitivity within the survey region is non-uniform. For this reason, in the following we restrict our attention to the region of Galactic longitude $|l| < 40^\circ$ only, within which the sensitivity for point sources is quite homogeneous and always at the level of at least $\approx 1.5$ percent of the Crab level (i.e. $F(>1\ TeV) \approx 3.4 \times 10^{-11}\ cm^{-2}\ s^{-1}$).

The number of TeV gamma-ray sources in the HESS Source Catalog within the region we selected ($|l| < 40^\circ, |b| < 3^\circ$) and with a flux above 1.5 percent of the Crab is 35. Notably, three of them are associated with the SNR shells RX J1713.7–3946, HESS J1731–347 and CTB 37B. While in the first two cases the association between an SNR shell and a gamma-ray source is firm, in the latter case both an association with an SNR shell (Aharonian et al. 2008c) and with a magnetar (Halpern & Gotthelf 2010) has been put forward. However, since CTB 37B still remains a possible candidate of a TeV-bright SNR shell, we consider it as such in the following. When needed, we will discuss how this uncertain association might affect our conclusions. The physical properties of these three sources are listed in Table 3.

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2 www.mpi-hd.mpg.de/hfm/HESS/pages/home/sources/
In addition to that, other three sources, CTB 37A, HESS J1745-303 and W28, are or might be associated with SNR shells in interaction with massive molecular clouds. However, the gamma-ray emission from these interacting systems might have a different origin than the one we investigate here. For example, the gamma-ray emission from the old SNR W28 (the estimated age is a few times $10^3$ yr) has been interpreted as the results of the interactions of CRs that escaped the SNR and penetrated into the molecular cloud (Gabici et al. 2010; Nava & Gabici 2012). Also the SNR coincident with the gamma-ray source HESS J1745-303 is believed to be quite old (more than $\approx 10^4$ yr; Aharonian et al. 2008b), and thus also in this case an interpretation of the gamma-ray emission in terms of escaping CRs (Gabici, Aharonian & Casanova 2009) or of re-acceleration of pre-existing CRs (the so called cloud-crushed model, Uchiyama et al. 2010) might be preferred. The situation is different for the SNR CTB 37A, which is likely to be young ($\approx 1-3 \times 10^3$ yr; Aharonian et al. 2008d) and thus in this case the gamma-ray emission might be related to the ongoing acceleration of CRs at the SNR shock, though the presence of the cloud might significantly affect the general picture of diffusive shock acceleration described in Section 2.2. However, the gamma-ray emission from CTB 37A can also be attributed to a pulsar wind nebula present in the region. For these reasons, we do not consider these three objects in the following.

Finally, 17 out of the 35 TeV sources detected by HESS in the region considered here, still remain unidentified.\footnote{In the absence of complete catalogues of TeV sources, and of thorough cross-correlations between TeV sources and SNR catalogues, we decided to adopt the classification of TeV sources in shells, shells interacting with molecular clouds, and unidentified sources as in the TeVCat online list of TeV sources, maintained by S. Wakely and D. Horan http://tevcat.uchicago.edu/} Thus, we can conclude that the number of SNRs detected in TeV gamma-rays in the considered region spans from a pessimistic tally of $\approx 3$ (if only the three isolated shells listed in Table 3 are considered) to an overoptimistic one of $\approx 20$ (in the unlikely event that most or all of the unidentified HESS sources are indeed SNRs).

To compare these numbers with our predictions we run 1000 Monte Carlo realizations of the supernova explosions in the Galaxy and compute the number of sources expected to be detected by HESS within the region in exam. A sensitivity at the level of 1.5 per cent of the Crab flux has been adopted for point like sources, while for extended ones the sensitivity has been degraded by a factor of $\theta_\text{APSM}/\theta_\text{PSF}$, where $\theta_\text{APSM}$ is the source apparent size and $\theta_\text{PSF} \approx 0.1^{\circ}$ is the angular resolution of HESS.\footnote{A discussion of the procedure to determine the extension of a TeV source clearly goes beyond the scope of this paper. However, it is important to remind that the classification of a sources as extended may depend on several factors, including the available photon statistics. The value 0:1 adopted here must be considered as an indicative figure only.} The results of this computation are shown in the top panel of Fig. 4, where the mean number of expected detections is plotted as a function of the spectral slope $\alpha$ of accelerated particles. Black and red lines correspond to $K_{\text{ep}} = 10^{-3}$ and $10^{-2}$, respectively. The other panels (top to bottom) show, for the case $K_{\text{ep}} = 10^{-2}$ the distance, age and angular size of the detected SNRs. Median values of these quantities are shown for all SNRs and for spatially resolved ones with a solid and dashed thick line, respectively. The thin dashed lines represent the maximum value for these quantities (averaged over the Monte Carlo realizations). In the bottom panel, the fraction of point-like sources is also shown as a black dotted line.

\begin{table}
\centering
\caption{Gamma-ray fluxes, distances, ages and apparent sizes of the three SNR shells detected by HESS in the region $|l| < 40^{\circ}$, $|b| < 3.5^{\circ}$ at a flux level above 1.5 per cent of the Crab. References: (1) Aharonian et al. (2006b); (2) Moriguchi et al. (2005); (3) Wang et al. (1997); (4) Abramowski et al. (2011); (5) Tian et al. (2008); (6) Aharonian et al. (2008c); (7) Nakamura et al. (2009).}
\begin{tabular}{lcccccc}
\hline
Name & $F(>\text{1 TeV})$ & $d$ & Age & Radius & Ref. \\
& ($10^{-12}$ cm$^{-2}$ s$^{-1}$) & (kpc) & (kry) & ($^{\circ}$) & \\
\hline
RX J1713.7-3946 & 15.5 & 1 & 1.6 & 0.65 & 1,2,3 \\
HESS J1731-347 & 6.9 & 2.4-4 & 27 & 0.25 & 4,5 \\
CTB 37B & 0.4 & 13.2 & 0.3-3 & 0.03 & 6,7 \\
\hline
\end{tabular}
\end{table}
Also the electron-to-proton ratio $K_{ep}$ can be constrained. We repeated the simulations described above for a value of $K_{ep}$ equal to 0.1 and we obtained a number of detections in the considered region of the Galactic disc of $\approx 54^{+7}_{-12}$ and $\approx 9^{+3}_{-4}$ for a spectral slope of $\alpha = 4.1$ and 4.4, respectively. This implies that values of $K_{ep}$ significantly larger than $10^{-2}$ are in conflict with observations, unless a quite steep spectrum for the accelerated particles is assumed.

We can now consider some of the physical quantities that characterize the SNRs observed in TeV gamma-rays, and compare their observed values with the ones predicted by our simulations. Here, we focus our attention on the distance of the SNRs, their age, and the angular extension of the gamma-ray emission. Two things have to be noted. First, only a handful of SNRs have been detected by HESS in the region of the sky we consider here, and secondly, many unidentified TeV sources (some of which might be in principle associated with SNRs) are present in the same region. Thus, some caution is needed when interpreting the results of the comparison.

The three bottom panels of Fig. 4 refer to the case $K_{ep} = 10^{-2}$, and show the median and maximum values of the three above-mentioned quantities (top to bottom): distance, age and apparent angular size (diameter) of the SNRs that should have been detected by HESS in the region we are considering. Thick red lines show the median values for all those SNRs (dashed lines) and for spatially resolved ones (solid lines), i.e. with an angular size larger than $\approx 0.1$. The thin dashed lines show the maximum value for these quantities, averaged over the number of Monte Carlo Realizations.

The median distance of detected SNRs lies, for all the values of the spectral slope $\alpha$, in the range $5 \lesssim d < 10$ kpc, which means that in the majority of the cases the detected SNRs are closer than the Galactic Centre. The median distance is slightly smaller ($d \approx 5$ kpc) if only resolved sources are considered, as expected given the worse instrument sensitivity in detecting extended sources, and given that it is easier to resolve nearby sources. On the other hand, the maximum distance up to which SNRs are detected – a sort of horizon for the detection of SNRs – is $\approx 15$ kpc for hard particle spectra ($\alpha \approx 4$) and decreases gradually for steeper and steeper spectra reaching a value of $\approx 10$ kpc for $\alpha = 4.4$.

The predicted median age of the SNRs detectable by HESS is quite insensitive to the value of $\alpha$, and is of the order of $\lesssim 5$ kyr. This slightly increases to $\gtrsim 5$ kyr if only resolved SNRs are considered. This is expected, given that older SNRs are obviously larger than younger ones. Also in this case, the maximum age of the detected SNRs is predicted to decrease from $\approx 20$ to $\approx 12$ kyr when the spectral slope of accelerated CRs goes from $\alpha = 4.1$ to 4.4.

Finally, the predicted fraction of point-like SNRs is in the range $0.4-0.6$, as indicated by the black dotted line in the bottom panel of Fig. 4. Amongst extended sources, the expected median angular size is $\approx 0.2$, while the largest detectable sources have a size of $\approx 1' - 1.2$. All these quantities are quite insensitive to the value chosen for $\alpha$.

Though a rigorous comparison between our predictions and available data is not easy, it is evident that a qualitative agreement between data and predictions exists. First of all, our expectations for the selected region of the HESS scan seem to reproduce correctly the actual number of detections (see the top panel in Fig. 4). Moreover, as already discussed in Section 3, also the number of very bright (flux at the level of $\approx 10^{-11}$ cm$^{-2}$ s$^{-1}$) SNRs detectable in the whole Galaxy seems to be well reproduced. All these facts are encouraging and provide additional support to the consistency of the SNR paradigm for the origin of CRs.

Due to the low number of detections, it is less straightforward to interpret our results on the median distance, age and size of TeV-bright SNRs. From a comparison between our predictions (see Fig. 4) and available data (see Table 3) it seems that the typical distances, ages and apparent sizes of the gamma-ray bright SNRs as predicted within our approach are in quite good agreement with observed quantities. The agreement between the predicted and the observed distances of SNRs worsens if the gamma-ray source coincident with CTB 37B (which is not unambiguously identified as an SNR) is not considered. In this case, the predicted median distance is larger than the observed ones, though it is difficult to draw firm conclusions based on few objects only. A summary of the main findings for the different scenarios considered in this paper can be found in Table 4.

We conclude the section with two more predictions of our calculations. The first one concerns the fraction of gamma-ray bright SNRs whose emission is dominated by hadronic processes. This fraction, as can be seen from Table 4, depends quite strongly on the adopted parameters (especially on the magnetic field strength). It can range from $\approx 60$ to 100 per cent. Determining the hadronic or leptonic origin of the gamma-ray emission from a given SNR is a very difficult task. Consider, for example, the three SNR listed in Table 3. While multiwavelength observations of RX J1713.7–3946 seem to point towards a leptonic origin of the gamma-ray emission (but see Fukui et al. 2012 for an alternative explanation), for the other two SNRs the situation is still ambiguous. Thus, if the commonly accepted interpretation of the observations of RX J1713.7–3946 is correct, at least for some SNRs the detected gamma-ray emission must be leptonic, and this would disfavour models M1 and M3, for which the electron-to-proton ratio is very small ($K_{ep} = 10^{-5}$), and also model M4 for which a very large magnetic field has been assumed. The second prediction is the fact that a very large fraction (about 80 percent for model M5, about 65 percent for model M2) of the SNRs which are expected to be detected in TeV gamma-rays are of Type Ia. The difficulty of detecting core-collapse supernovae is connected to the fact that the SNR shock propagates in the tenuous medium of the wind-blown bubble, which strongly reduces the

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**Table 4.** Expected number of detections in the region considered in Fig. 4 and SNR properties for the different models listed in Table 2.

| Model | M1 | M2 | M3 | M4 | M5 | M6 |
|-------|----|----|----|----|----|----|
| Mean (median) number of detections | 0.9(2) | 1.8(3) | 5.3(6) | 5.9(6) | 6.6(7) | 22(23) |
| Median distance (kpc) | 2.6 | 2.7 | 5.0 | 5.3 | 5.0 | 8.7 |
| Median age (kyr) | 1.8 | 1.0 | 4.2 | 3.0 | 2.8 | 4.2 |
| Median apparent size (°)* | 0.25 | 0.28 | 0.22 | 0.26 | 0.22 | 0.20 |
| Fraction of point sources | 0.34 | 0.41 | 0.40 | 0.51 | 0.40 | 0.55 |
| Fraction of hadronic sources | 1 | 0.59 | 1 | 0.98 | 0.87 | 0.71 |

*Extended sources only (i.e. size larger than 0.1).
gamma-ray emission due to proton–proton interactions (the core-collapse SNRs which are expected to be detected in gamma-rays are characterized by a dominant leptonic emission). Determining the type of the progenitor supernova is a very difficult task. Amongst TeV-bright SNRs, only a few are firmly identified as thermonuclear or core-collapse supernovae. From the detection of the light echoes of the supernova explosions, Tycho was firmly identified as a Type Ia supernova (Krause et al. 2008b), while Cas A as a Type IIb (Krause et al. 2008a). Also SN 1006 is confidently identified as a Type Ia supernova due to its location quite distant from the Galactic disc (e.g. Stephenson 2010). For the other TeV SNRs the situation is less clear, though some hints were provided in some cases (see e.g. Tian et al. 2010), and thus more efforts are needed in order to increase the number of firm identifications of the supernova type.

5 DISCUSSION OF THE RESULTS

In this section, we investigate how the results obtained in this paper change when different assumptions are made on the values of some key physical parameters.

One of the most important quantities involved in our calculations is the global CR luminosity of the Galaxy, \(L_{\text{CR}}^{\text{MW}}\), which represents the total energy output from all the sources of CRs in the Galaxy. If SNRs are the main sources of CRs, then from the supernova rate in the Galaxy \(v_{\text{SN}}\) it is possible to constrain the typical amount of energy that each SNR must convert into CRs (see equation 17). The CR luminosity of the Galaxy is determined by modelling the escape of CRs from the Galaxy, and different approaches lead to very similar values of this quantity, which is of the order of \(L_{\text{CR}}^{\text{MW}} \approx 10^{41}\) erg s\(^{-1}\) (e.g. Dogiel et al. 2002; Strong et al. 2010). However, an uncertainty up to a factor of \(\approx 2\) might still be accepted. For this reason, we repeat our calculations for three values of \(L_{\text{CR}}^{\text{MW}}\), namely, \(5 \times 10^{40}\), \(10^{41}\) and \(2 \times 10^{41}\) erg s\(^{-1}\), and, as done in Section 4, we compute the expected mean number of SNRs detectable within the HESS survey of the Galactic disc in the Galactic longitude and latitude ranges \(|l| < 40^\circ\) and \(|b| < 3^\circ\), and with integral flux above 1.5 per cent of the Crab. For the three values of \(L_{\text{CR}}^{\text{MW}}\) discussed above, the mean number of detections scales roughly linearly and reads 3.1, 6.6 and 11, respectively (for model M5 in Table 2). The approximate linearity between the average number of detections and the CR power in the Galaxy can be easily understood as follows: if we keep all the other parameters unchanged, the effect of varying the global CR luminosity is reflected into a different acceleration efficiency \(\eta_{\text{CR}}\) that the SNRs must achieve in order to sustain the CR intensity in the Galaxy. If \(L_{\text{CR}}^{\text{MW}}\) is increased by a factor of \(f\), then also the acceleration efficiency \(\eta_{\text{CR}}\) is augmented by the same factor, as well as the expected gamma-ray luminosity from each SNR. This in turn implies that SNRs would be visible by the same telescope up to distances \(d\) a factor of \(\approx f^{1/2}\) larger, or, if as a first approximation we assume SNR to be homogeneously distributed in a flat disc, within a volume a factor of \(\propto d^2\propto f\) larger, which explains the linearity.

Note that an identical linear scaling has to be expected also if we relax the assumption of equality \(\eta_{\text{CR}} \approx \epsilon_{\text{CR}}\) between the two CR acceleration efficiencies defined in Section 2.2 and we substitute it with the expression \(\eta_{\text{CR}} = \epsilon_{\text{CR}}\), where \(f\) accounts for possible deviations from the equality. However, as already said above, theoretical investigations indicates that \(f\) should be quite close to 1 (Caprioli 2012; Zirakashvili & Ptuskin 2012), and thus the predictions reported here can be regarded as fiducial estimates, easy to be rescaled for possibly different values of \(f\).

Another crucial parameter is the supernova explosion rate in the Galaxy, \(v_{\text{SN}}\). We adopt throughout the paper a value of \(v_{\text{SN}} = 3\) per century, in agreement with recent estimates (e.g. Li et al. 2011). However, also in this case a systematic uncertainty of a factor of \(\approx 2\) is expected (Li et al. 2011). If we repeat the estimate of the mean number of detections (model M5, \(|l| < 40^\circ\)) for explosion rates in the range \(v_{\text{SN}} = 1\)–3 per century we do not obtain any significant difference in the predicted number of detections. This can be understood by noting that a change in the supernova rate also affects the CR acceleration efficiency per SNR. If the rate of supernova explosions \(v_{\text{SN}}\) is multiplied by a factor of \(f\), the acceleration efficiency per SNR (and thus its gamma-ray emission) has to be multiplied by the inverse factor \(f^{-1}\), in order to keep the CR luminosity in the Galaxy constant. In other words, there will be \(f\) more SNRs that contribute to the CR intensity in the Galaxy, but each SNR will be a factor of \(f\) less powerful in gamma-rays, and thus visible within a volume a factor of \(f\) smaller. And this explains why our predictions are quite insensitive to the choice of the parameter \(v_{\text{SN}}\). This can be restated in another way: if we reduce \(v_{\text{SN}}\), the fraction of SNRs that can be detected by a given instrument is larger, even if the total number of detections is unchanged.

Also the value of the magnetic field plays a crucial role and it is thus mandatory to investigate how our predictions change if different values of the field are assumed. A smaller magnetic field strength reduces the synchrotron losses of electrons that can thus radiate more gamma-ray photons through inverse Compton scattering. We considered the two-zone model (M5) and varied the intensity of the field in zone 2. The mean number of expected detections in this case goes from \(\approx 8.6\) to \(\approx 6.6\) if the field is assumed to vary from 5 to 40 \(\mu\)G. Moreover, the fraction of SNRs whose TeV emission is dominated by the hadronic component goes from 63 to 97 per cent.

We investigate now which effect has on our predictions a different assumption concerning the maximum energy up to which particles can be accelerated at SNR shocks. The estimates for the maximum energy given in equations (12) and (13) are very plausible guesses, but it is true that we are far from having a solid knowledge of the details of the amplification mechanism of the magnetic field that determines the maximum particle energy at a shock. A way to change the value of the maximum energy of accelerated particles is to change the size of the CR shock precursor, i.e. the value of the parameter \(\xi\) in equation (7). If we go from \(\xi = 0.1\) to \(\xi = 0.05\) we reduce by a factor of 2 both the size of the precursor and the value of the maximum energy. The number of expected detections is, in the two cases, \(\approx 6.6\) and \(\approx 5\), respectively. Thus, we can conclude that our predictions are not much affected, unless the assumed values for the maximum particle energy are varied significantly (more than a factor of 2).

Finally, we checked for the stability of our predictions against variations of the spatial distribution of SNRs and gas in the Galaxy. We repeated the procedure for a spatial distribution of SNRs with and without taking into account the presence of spiral arms, and we used the radial distribution of SNRs given by Case & Bhattacharya (1998) instead of the one by Lorimer (2004) and did not found any significance variation in our predictions. This is connected to the fact that SNRs can be detected up to quite large distances, of the order of \(\approx 10\)–15 kpc (see Fig. 4), and thus the effects of different spatial distributions are not that important. We also used cylindrical symmetric templates for the gas distribution in the Galaxy (as in Shibata et al. 2011), without finding an appreciable effect. However, it has to be noted that the surveys of CO and HI that are used to infer the gas distribution in the Galaxy are characterized by a spatial resolution along the line of sight of \(\approx 50–100\) pc. This might create problems, for examples, in identifying dense molecular clouds which have a typical size well below 100 pc.
The presence of dense molecular clouds in the vicinity of SNRs might in principle affect significantly our results because it would enhance the expected hadronic gamma-ray emission from those SNRs interacting with clouds. This fact is relevant for core-collapse supernovae, which generally explode in young stellar clusters or associations, which are in turn embedded into molecular clouds (e.g. Garmany 1994). The collective effect of the dense winds from the supernova progenitor stars would be to inflate a cavity (generally referred to as superbubble) and remove most of the gas. However, dense clumps of gas, ubiquitous in molecular clouds, cannot be swept up by the stellar winds, remain inside the superbubble and can thus be subject to interactions with SNRs (e.g. Parizot et al. 2004). Though providing a quantitative estimate of this effect is not a straightforward task, we note that the effect of dense gas clumps would be a systematic increase of the hadronic gamma-ray emission from some core-collapse SNR, which is to say a systematic increase of the number of predicted detections of SNRs in TeV gamma-rays. It is interesting to note that this fact would make some of the claims made in this paper even stronger. For example, we showed in Section 4 that hard spectra of accelerated CRs (with slope $\alpha \approx 4.1$ or harder) and/or large values of the electron-to-proton ratio ($K_{\text{ep}}$ significantly larger than $\approx 10^{-2}$) are in conflict with observations because they would imply a too large number of detections. The presence of dense gas clumps would further increase the predicted number of detections, making these two claims even more solid, and would call for even steeper spectra and/or smaller values of the electron-to-proton ratio.

However, a qualitative argument can be provided to suggest that the effect of gas clumps may not be a major one. In fact, we know from observations that SNRs in interaction with molecular clouds are generally quite old, with ages of the order of $\approx 10^3$ yr or more (e.g. Uchiyama et al. 2010), while the majority of the SNRs for which we predict a detectable TeV emission have an age well below 5 kyr (see Fig. 4). It is not clear whether such old SNRs are capable of accelerating particles up to energies well above $\approx 10$ TeV, as needed in order to produce $\approx 10^3$ TeV photons. According to our current knowledge of the shock acceleration mechanism, which we briefly reviewed in Section 2.2, it seems that old SNRs can, at best, marginally reach these energies. This suggests that, in this respect, our predictions can still be considered solid and reliable.

6 CONCLUSIONS

In this paper, we performed a comparison between the expectations of the SNR paradigm for the origin of Galactic CRs and the available data in the TeV energy domain. Instead of proceeding on a case-by-case study of individual SNRs, we aimed at studying TeV-bright SNRs as a population. To our knowledge, this is the first time that such an approach is performed.

We started by assuming that SNRs are the main sources of CRs, and this allowed us to estimate the typical CR acceleration efficiency per SNR. We then used a Monte Carlo approach to simulate the position and time of explosions of the SNRs in the whole Galaxy and we computed then the expected number of SNRs that should be detected in the TeV domain by the present generation of Cherenkov telescopes. To compare our predictions with data, we selected a region of the Galactic disc with Galactic longitude $|l| < 40^\circ$, for which HESS performed a scan with a roughly spatially homogeneous exposure, corresponding to a sensitivity of $\approx 1.5$ per cent of the Crab. Predictions seem to agree well with available data, thus providing an additional consistency check of the idea that SNRs are the sources of CRs.

Our main findings can be summarized as follows: first of all, we obtained evidence for the fact that particle spectra significantly steeper than $\alpha = 4$ have to be accelerated at SNRs, if they indeed are the sources of CRs. The reason for that is the fact that hard spectra ($\alpha \approx 4$) would result in a very strong TeV luminosity and this would be inconsistent with the scarce number of SNRs currently detected at TeV energies. Secondly, the expected fraction of gamma-ray bright SNRs whose emission is dominated by neutral-pion decay strongly depends on the assumptions made on the strength of the magnetic field. For the range of parameters investigated in Section 4 this fraction spans from $\approx 60$ to 100 per cent, and the largest values are obtained either for a very low electron-to-proton ratio or for a very large magnetic field strength (one of the two conditions suffices to increase the fraction up to $\approx 100$ per cent). The fact that there is at least one SNR (namely RX J1713.7$-$3946) whose gamma-ray emission is commonly ascribed to inverse Compton scattering might suggest that an high electron-to-proton ratio (of the order of $K_{\text{ep}} \approx 10^{-2}$) characterizes the acceleration of particles at SNRs and that regions where the field strength is not too large must exist in SNRs. Finally, according to our predictions we should expect to detect the same number of extended and point-like (where with point-like we intend sources with a size smaller than 0.1) TeV-bright SNRs, and supernovae of Type Ia should account for a large fraction of the detections ($\approx 60$–80 per cent).

Before concluding we comment on a possible extension of the procedure described in this paper to the GeV energy domain, currently probed by the Fermi and Agile satellites. A constantly increasing number of SNRs is being detected in the GeV energy band. Several of these SNRs are quite old, often radiative systems that show clear signatures of interactions with massive molecular clouds (Uchiyama et al. 2010). For these systems, not considered here, the scenario of particle acceleration and gamma-ray production is most likely very different from the one considered in this paper (see e.g. Gabici, Aharonian & Casanova 2009; Uchiyama et al. 2010; Malkov, Diamond & Sagdeev 2011). Despite this fact, we can anyway use the procedure developed in this paper, and keep in mind that the estimates obtained in this way in the GeV domain would be very approximate, and most likely lower limits only (because it will not take into account the old interacting systems). By considering a sensitivity for Fermi (integrated above 1 GeV) of few $10^{-9}$ cm$^{-2}$ s$^{-1}$ in the inner Galaxy (where most of the detections are likely to happen), we obtain a number of expected detections of the order of several tens.

In a forthcoming publication (Cristofari et al., in preparation), the procedure developed in this paper will be used to estimate the impact that the next generation Cherenkov Telescope Array will have on the studies of acceleration of CRs at SNR shocks.

ACKNOWLEDGEMENTS

We thank E. de Oña Wilhelmi, A. Djannati-Atai, F. Giordano, D. Maurin, G. Morlino, L. Nava and M. Renaud for helpful discussions. SG, RT and EP acknowledge support from ANR under the JCJC Programme. SG also acknowledges support from the EU [FP7 – grant agr. n. 256464]. SC acknowledges support from the city of Paris under the programme ‘Research in Paris’. RT acknowledges support under the Labex UnivenS.

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