Cosmic rays in star-forming galaxies

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Abstract.

The energy density of cosmic ray protons (CRp) in star-forming environments can be measured from $\gamma$-ray $\pi^0$-decay emission, (ii) inferred from the measured radio non-thermal synchrotron emission (once a theoretical p/e ratio and particle-field equipartition have been assumed), and (iii) estimated from the observed supernova rate and the deduced CRp residency time. For most of the currently available galaxies where these methods can be simultaneously applied, the results of the various methods agree and suggest that CRp energy densities range from $\mathcal{O}(10^{-1})$ eV cm$^{-3}$ in very quiet environments up to $\mathcal{O}(10^2)$ eV cm$^{-3}$ in very active ones. The only case for which the methods do not agree is the Small Magellanic Cloud, where the discrepancy between measured and estimated CRp energy density may be due to a smaller characteristic CR confinement volume.

1. Introduction

Active star formation in galaxies leads to production of CR protons and electrons via the Fermi-I diffusive shock acceleration mechanism in supernova (SN) remnants. Basic considerations suggest that the timescales required for CRp to be Fermi-I accelerated ($\tau_+$) and to lose energy via pion decay into photons and $e^+e^-$ pairs or via advection by bulk outflows ($\tau_-$) are shorter than the timescale of starburst activity in galaxies ($\tau_{SB}$), which is roughly comparable to a dynamical timescale. Consequently, in a starburst region a rough balance can be achieved between energy gains and losses for galactic CRs during a typical burst of star formation. Under equilibrium conditions in a galaxy, a minimum-energy configuration of the magnetic field and the CRs may be attained. This implies that energy densities of particles and magnetic fields may be in approximate equipartition.

The equipartition assumption enables deduction of the CRp energy density, $U_p$ (which essentially measures the particle energy content), from the relatively easily observable synchrotron radio emission. In this radio-based approach, $U_p$ can be estimated if the source’s size, distance, radio flux, and radio spectral index are known, and particle-field equipartition and a p/e ratio are assumed.

In the $\gamma$-based approach, $U_p$ can be obtained from numerically fitting the GeV-TeV spectral flux, which is mostly due – via $\pi^0$ decay – to CRp interactions with ambient gas protons, based on the solution of the diffusion-loss equation for accelerated CR particles. Only recently have such measurements become possible – and only for ten sources to date.
### Table 1. Star-forming galaxies: the data.

| Object       | $D_e^{[1]}$ (Mpc) | $r_e^{[2]}$ (kpc) | $f_1^{[3]}$ (Jy) | $\alpha_{NT}^{[4]}$ | $\dot{\nu}_{SN}^{[5]}$ (yr$^{-1}$) | $M_{\text{gas}}^{[6]}$ ($M_\odot$) | $L_\gamma^{[7]}$ (erg s$^{-1}$) | $\tau_{\text{res}}^{[8]}$ (yr) | Notes |
|--------------|------------------|------------------|-----------------|------------------|-----------------------------|-----------------|------------------|------------------|-------|
| Arp 220     | 74.7             | 0.25             | 0.3             | 0.65             | 3.5                         | 9.24            | <42.25           | 9.0E+3           | SB    |
| M82         | 3.4              | 0.26             | 10.0            | 0.71             | 0.25                        | 9.37            | 40.21            | 2.6E+3           | SB    |
| NGC 253     | 2.5              | 0.20             | 5.6             | 0.75             | 0.12                        | 9.20            | 39.76            | 2.0E+4           | SB    |
| Milky Way   | –                | 4.4              | –               | –                | 2E-2                        | 9.81            | 38.91            | 2.7E+7 quiescent |       |
| M31         | 0.78             | 5.17             | 4.8             | 0.88             | 1E-2                        | 9.88            | 38.66            | 4.0E+7 quiescent |       |
| M33         | 0.85             | 2.79             | 3.30            | 0.95             | 3E-3                        | 9.35            | <38.54           | 2.6E+7 quiescent |       |
| LMC         | 0.049            | 3.0              | 285.0           | 0.84             | 2E-3                        | 8.86            | 37.67            | 1.0E+7           | quiescent |
| SMC         | 0.061            | 1.53             | 45.3            | 0.85             | 1E-3                        | 8.66            | 37.04            | 4.0E+7           | quiescent |

[1] Distance (from Abdo et al. 2011).
[2] Effective radius of star-forming region. See text. Data are from Persic & Rephaeli 2010 and refs. therein (Arp 220, M82, NGC 253), Beck & Gräve 1982 (M31), Tabatabaei et al. 2007 (M33), Weinberg & Nikolaev 2001 (LMC), and Wilke et al. 2003 (SMC).
[3] 1 GHz flux density. Data are from Persic & Rephaeli 2010 and refs. therein (Arp 220, M82, NGC 253), Beck & Gräve 1982 (M31), Tabatabaei et al. 2007 (M33), Klein et al. 1989 (LMC), and Haynes et al. 1991 (SMC).
[4] Non-thermal spectral radio index. Data are from Persic & Rephaeli 2010 and refs. therein (Arp 220, M82, NGC 253), Beck & Gräve 1982 (M31), Tabatabaei et al. 2007 (M33), Klein et al. 1989 (LMC), and Haynes et al. 1991 (SMC).
[5] SN rate. Data are from Persic & Rephaeli 2010 and references therein (Arp 220, M82, NGC 253), Diehl et al. 2006 (Milky Way), and van den Bergh & Tammann 1991 (M31, M33, SMC, LMC; see also Pavlidou & Fields 2001).
[6] Gas mass (neutral plus molecular hydrogen: $M_{\text{HI}} + M_{\text{H}_2}$), in log. Data are from: Torres 2004 for Arp 220; Abdo et al. 2010a for M82, NGC 253, and the Milky Way; Abdo et al. 2010b for M31 and M33; Abdo et al. 2010c for the LMC; and Abdo et al. 2010d for the SMC.
[7] High-energy ($>100$ MeV) $\gamma$-ray luminosity, in log (from Abdo et al. 2011).
[8] CRp residency time.

In the **SN method**, once a fraction of SN kinetic energy that is channeled into particle acceleration is assumed, $U_p$ can be estimated if the size of the star-forming region, and the SN rate there, are known – and if the CRp residency timescale can be evaluated from the presence (or lack) of a galactic wind emanating from the star-forming region and from the gas density there. The residency timescale is dominated by the advection timescale ($\sim 10^5$ yr) in high-SFR (starburst) galaxies and by the $pp$-generated $\pi^0$-decay timescale ($\sim 10^7$ yr) in low-SFR (quiescent) galaxies. (Both CRp energy loss timescales are lower than the typical starburst timescale, $\tau_{SB} \sim 10^8$ yr.)

Expanding on a previous paper (Persic & Rephaeli 2010), here we show that the three methods give consistent results on $U_p$ for a sample of 8 galaxies with widely varying levels of star formation activity from very quiescent to extreme starbursts. These are the only galaxies of their kind for which $\gamma$-ray data (plus radio data and SN rates) are available (see Table 1). After reviewing the radio, $\gamma$-ray, and SN methods (sect. 2,3,4), the corresponding values of $U_p$ are inferred for our sample galaxies in sect. 5. The results are discussed in sect. 6 and summarized in sect. 7.
2. Particles and magnetic field.

CRe populations consist of primary (directly accelerated) and secondary (produced via charged pion decays) electrons. Their combined spectral density distribution is assumed to be a single power-law of the Lorentz factor, $\gamma$, in some interval $\gamma_1 \leq \gamma \leq \gamma_2$

$$N_e(\gamma) = N_{e,0} (1 + \chi) \gamma^{-q}$$  \hspace{1cm} (1)

where $N_{e,0}$ is a normalization factor of the primary electrons, and $\chi$ the secondary-to-primary electron number density ratio.

Electron synchrotron emission from a region with radius $r_s$ (i.e., the radius of a same-volume sphere) and mean magnetic field $B$, located at a distance $d$, is

$$f_\nu = 5.67 \times 10^{-22} \frac{r_s^2}{d^2} N_{e,0} (1 + \chi) a(q) B^{\frac{q+1}{2}} \left( \frac{\nu}{4 \times 10^6} \right)^{-\frac{q+1}{2}} \text{erg/}(s\text{ cm}^2\text{Hz})$$  \hspace{1cm} (2)

where $a(q)$ is defined and tabulated in, e.g., Tucker (1975). Setting

$$\psi \equiv \left( \frac{r_s}{0.1 \text{kpc}} \right)^{-3} \left( \frac{d}{\text{Mpc}} \right)^2 \left( \frac{f_{1\text{GHz}}}{\text{Jy}} \right)$$

and $\nu = 1 \text{GHz}$, the normalization of the electron spectrum is

$$N_{e,0} = \frac{5.72}{1 + \chi} \times 10^{-15} \psi a(q)^{-1} B^{\frac{q+1}{2}} 250^{\frac{q-1}{2}}$$  \hspace{1cm} (4)

A second relation is required to separately estimate $N_e$ and $B$. This is provided by the condition of equipartition between particles (electrons and protons) and the magnetic field, $U_p + U_e \simeq B^2/8\pi$, which could possibly be attained due to a high degree of coupling between all the relevant degrees of freedom in the starburst region. In terms of the proton-to-electron energy density ratio, $\kappa(q)/(1 + \chi) = U_p/U_e$, equipartition translates to

$$U_p \left[ 1 + \frac{1 + \chi}{\kappa(q)} \right] \simeq \frac{B^2}{8\pi}$$  \hspace{1cm} (5)

The electron energy density is $U_e = N_{e,0} (1 + \chi) m_e c^2 \int_{\gamma_1}^{\gamma_2} \gamma^{1-q} d\gamma$. An approximate expression for $U_e$ is obtained by ignoring the contribution of low energy electrons with $\gamma < \gamma_1$: while the change of spectral slope at $\gamma < \gamma_1$ is important as it marks the transition from synchrotron to Coulomb losses (due to Coulomb interactions of the CRe with gas particles; see Rephaeli 1979 and Sarazin 1999), for our purposes here we consider only the spectrum above $\gamma_1$ which is directly deduced from radio measurements. In our approximate treatment here we assume $\gamma_1 = 10^3$ in all regions of interest, a possible simplification given that our numerical estimates depend only relatively weakly on the exact value of $\gamma_1$. Under this assumption, the electron energy density is $U_e = N_{e,0} (1 + \chi) m_e c^2 \int_{\gamma_1}^{\gamma_2} \gamma^{1-q} d\gamma$, where $\gamma_2$ is an upper cutoff whose exact value is irrelevant in the applicable limit $\gamma_2 \gg \gamma_1$. For $q > 2$ and $\gamma_2 \gg \gamma_1$, $U_e \simeq N_{e,0}(1 + \chi)m_e c^2 \gamma_1^{2-q}/(q - 2)$, which upon substitution of the expression for $N_{e,0}(1 + \chi)$ from Eq.(4) yields

$$U_e = \frac{2.96}{(1 + \chi)} \times 10^{-22} 250^2 \psi \frac{\gamma_1^{2-q}}{(q - 2) a(q)} B^{\frac{q+1}{2}}.$$  \hspace{1cm} (6)

Using Eq.(5), we then get the equipartition magnetic field

$$B_{eq} = \left[ \frac{7.44 \times 10^{-21}}{1 + \chi} \left( 1 + \frac{\kappa(q)}{1 + \chi} \right) \frac{\gamma_1^{2-q}}{(q - 2) a(q)} \right]^{\frac{1}{2}}.$$  \hspace{1cm} (7)
The ratio $\chi$ is a function of energy; it depends on the injection $p/e$ number ratio, $p/e$, which generally depends on the injection slope (e.g., Schlickeiser 2002), and on the gas optical thickness to $pp$ interactions (that produce neutral and charged pions). Because of the high gas density in the starburst region the production of secondary electrons is expected to be especially important there. Following Persic & Rephaeli (2010), in the rest of this paper we shall use $\chi = 0.5$ as a fiducial value for all galaxies, starburst and quiescent alike. This value approximately matches results of detailed numerical starburst models for energies $\gtrsim 10$ MeV (e.g., Rephaeli et al. 2010, and references therein).

Finally, using Eqs. (7,5) we readily obtain an explicit expression for $U_p$:

$$U_p = \frac{1}{8\pi} \left( 1 + \frac{\chi}{\kappa(q)} \right)^{-1} \left[ \frac{7.44 \times 10^{-21}}{1 + \chi} \right] \left( 1 + \frac{\kappa(q)}{1 + \chi} \right) \frac{\gamma^{2-q} 250^{\psi} \chi}{(q - 2) a(q)} \frac{1}{\psi}. \quad (8)$$

From Eq.(8), using the expression for the proton-to-electron energy density ratio, $\kappa(q)$, reported in (e.g.) Persic et al. (2008), and setting $\chi = 0.5$, numerical values of $U_p$ can be obtained from the relevant observational quantities for our sample galaxies (see Table 1): they are reported in Table 2.

3. Cosmic rays and $\gamma$-ray emission.

In this section we will review some basic features of the modeling of $\gamma$-ray emission from star-forming galaxies, and the status of HE/VHE $\gamma$-ray observations of the latter. Detections of several such galaxies have enabled measurements of $U_p$ values either in starburst cores or galaxy-wide.

In most starburst galaxies, such as the two nearby ones M82 and NGC 253, the central starburst region (also called the source region) with a radius of $\sim 200 - 300$ pc is identified as the main site of particle acceleration. Here, the injection particle spectrum is assumed to have the non-relativistic strong-shock index $q = 2$. A theoretical $N_p/N_e$ ratio, predicted from charge neutrality of the injected CRs, is likely to hold in this source region – as is also the assumption of equipartition. A measured radio index $\alpha \simeq 0.7$ in the source region implies $q = 2\alpha + 1 \simeq 2.4$ there. This indicates a substantial steepening of the CRe spectrum from the injection value $q_0 = 2$, due to diffusion ($D \propto \gamma^{-\delta}$) effects, that cause the steady-state particle spectral index to be $q_0 + \delta$ above some break energy.

Adopting the convection-diffusion model for energetic electron and proton propagation and accounting for all the relevant hadronic and leptonic processes, the steady-state energy distributions of these particles, in both the (active) starburst nucleus and the (passive) disk of these galaxies, can be determined with a detailed numerical treatment once the gas distribution is known (e.g., Torres 2004; Persic et al. 2008). The relevant energy loss processes are electron emissions by bremsstrahlung and Compton scattering by electrons, and $\gamma$-ray emission from $\pi^0$ decay following $pp$ collisions. Bremsstrahlung losses dominate at lower energies, whereas $\pi^0$ decay losses dominate at higher energies. In the GeV-TeV region, emission mainly comes from $pp$-induced $\pi^0$ decay (e.g., Rephaeli et al. 2010).

The procedure is similar when star formation is not undergoing a burst confined to the nuclear region but is proceeding more quietly and uniformly scattered over the whole disk.

For a source with ambient gas number density $n_{gas}$, proton energy density $U_p$, and volume $V$, the integrated hadronic emission from $pp$-induced $\pi^0$ decay is

$$L_{\geq E}^{[q]} = \int_V g_{\geq E}^{[q]} n_{gas} U_p \, dV \, s^{-1}, \quad (9)$$

with the integral emissivity $g_{\geq E}^{[q]}$ in units of photon $s^{-1} (\text{H-atom})^{-1} (\text{eV/cm}^3)^{-1}$ (Drury et al. 1994). Therefore $U_p$ can be determined, once $L_{\geq E}$ and $n_{gas}(r)$ are observationally known and...
the particles’ steady-state energy distributions have been numerically worked out by solving the convection-diffusion model for CRe and CRp propagation. By its very nature, this is a direct measurement of $U_p$.

The two local starburst galaxies M 82 and NGC 253 are the only non-AGN extragalactic sources that, up to now, have been detected in both the GeV (Abdo et al. 2010a) and TeV (Acciari et al. 2009; Acero et al. 2009) domains. The measured fluxes and spectra of both galaxies in the two bands agree with predictions of recent numerical models (see above) that have $U_p \approx O(10^2) \text{eV cm}^{-3}$ in the starburst nucleus. The highest-SFR galaxy in the nearby universe, Arp 220, was undetected by MAGIC (Albert et al. 2007).

HE $\gamma$-ray detections were obtained with the Large Area Telescope (LAT) on board the orbiting Fermi telescope for a number of low-SFR galaxies: (i) the Andromeda galaxy M 31 (Abdo et al. 2010b), with $U_p \approx 0.35 \text{eV cm}^{-3}$; (ii) the Large Magellanic Cloud (LMC) whose average spectrum, either including or excluding the bright star-forming region of 30 Doradus, suggests $U_p \approx 0.2 - 0.3 \text{eV cm}^{-3}$ (Abdo et al. 2010c); (iii) the Small Magellanic Cloud (SMC), whose integrated spectrum requires $U_p \approx 0.15 \text{eV cm}^{-3}$ (Abdo et al. 2010d). Only flux upper limits exist for the Triangulum galaxy M 33 (Abdo et al. 2010b).

For the Milky Way, the modeling of the Galactic diffuse HE emission along the lines outlined above requires an average $U_p \approx 1 \text{eV cm}^{-3}$ (Strong et al. 2010; Ackermann et al. 2011). This compares with $U_p \approx 1 \text{eV cm}^{-3}$ measured at the Earth’s position (e.g., Webber 1987), and with $(6 \pm 3) \text{eV cm}^{-3}$ in the $\sim 200 \text{pc}$ region of the Galactic center, as inferred from the measured VHE $\gamma$-ray emission (based on HESS data: Aharonian et al. 2006).

The $U_p$ values measured through GeV-TeV observations are reported in Table 2.

4. Supernovae and cosmic rays.

The SN origin of CRs was suggested early on. As a test of this hypothesis, we obtain an estimate of $U_p$ by combining the SN frequency with the residency timescale, $\tau_{\text{res}}$, of CR protons that give rise to HE emission in the star-forming region, and assuming a bona-fide value of the energy that goes into accelerating CR particles per SN event.

Two timescales define $\tau_{\text{res}}$:

(i) the energy-loss timescale for $pp$ interactions,

$$\tau_{\text{pp}} = (\sigma_{\text{pp}} n_p)^{-1} \tau$$

and

(ii) the CRp advection timescale, $\tau_{\text{adv}}$, describing the removal of CRs out of the disk mid-plane region in a fast ($v_{\text{out}} \sim 2500 \text{ km s}^{-1}$ for M 82: Strickland & Heckman 2009) starburst-driven wind, which for a homogeneous distribution of SNe within the starburst nucleus of radius $r_s$ writes

$$\tau_{\text{adv}} = 3 \times 10^4 \left( \frac{r_s}{0.3 \text{kpc}} \right) \left( \frac{v_{\text{out}}}{2500 \text{ km s}^{-1}} \right)^{-1} \text{yr}. \quad (11)$$

Thus,

$$\tau_{\text{res}}^{-1} = \tau_{\text{pp}}^{-1}(n_{\text{HI}}) + \tau_{\text{out}}^{-1}(r_s, v_{\text{out}}). \quad (12)$$

During $\tau_{\text{res}}$, a number $\nu_{\text{SN}} \tau_{\text{res}}$ of SN explode and deposit the kinetic energy of their ejecta, $E_{\text{ej}} = 10^{51} \text{erg per SN}$ (Woosley & Weaver 1995), into the interstellar medium. Arguments based on the CR energy budget in the Galaxy and SN statistics suggest that a fraction $\eta \sim 0.05 - 0.1$
of this energy is available for accelerating particles (e.g., Higdon et al. 1998). We then express the CRp energy density as:

\[ U_p = 85 \frac{\nu_{SN}}{0.3 \, \text{yr}^{-1}} \frac{\tau_{\text{res}}}{3 \times 10^4 \, \text{yr}} \frac{\eta}{0.05} \frac{E_{\text{ej}}}{10^{51} \, \text{erg}} \left( \frac{r_s}{0.3 \, \text{kpc}} \right)^{-3} \, \text{eV cm}^{-3}. \] (13)

5. Energy densities of CR protons in galaxies.

Regions in galaxies, that can be defined as active or passive with respect to CR acceleration and diffusion, can be either clearly separated or mixed up. For example, in M 82 and NGC 253 star formation goes on mainly in the nuclear region, so CRs are accelerated in the nucleus from where diffusion goes on mainly in the nuclear region, so CRs are accelerated in the nucleus from where the CRp energy density as:

\[ U_p = \frac{\nu_{SN}}{0.3 \, \text{yr}^{-1}} \frac{\tau_{\text{res}}}{3 \times 10^4 \, \text{yr}} \frac{\eta}{0.05} \frac{E_{\text{ej}}}{10^{51} \, \text{erg}} \left( \frac{r_s}{0.3 \, \text{kpc}} \right)^{-3} \, \text{eV cm}^{-3}. \] (13)

\[ \nu_{SN} \sim 0.25 \, \text{yr}^{-1} \quad \text{and} \quad \tau_{\text{res}} \sim \tau_{\text{adv}} \sim 3 \times 10^4 \, \text{yr} \quad \text{in the starburst nucleus, and} \quad v_{\text{adv}} \sim 2500 \, \text{km s}^{-1}; \] see Persic & Rephaeli 2010, from Eq.(13) we get \( U_p \sim 95 \, \text{eV cm}^{-3} \) (SN method).

M 82. Following Persic et al. (2008; and references therein) we take the central starburst to be a region with a radius of 300 pc and height of 200 pc, hence \( r_s = 260 \, \text{pc}, \) whose nonthermal radio emission has \( f_{1 \, \text{GHz}} = 10 \, \text{Jy} \) and \( \alpha = 0.71 \). The latter implies \( q = 2.42, \) that in turn implies \( a \approx 0.09 \) and \( \kappa \approx 10. \) From Eq.(8) we obtain \( U_p \sim 90 \, \text{eV cm}^{-3} \) in the starburst nucleus (radio method). Because \( \nu_{SN} = 0.25 \, \text{yr}^{-1} \) and \( \tau_{\text{res}} \sim \tau_{\text{adv}} \sim 3 \times 10^4 \, \text{yr} \) (being \( n_p \sim 10^2 \, \text{cm}^{-3} \), in the starburst nucleus, and \( v_{\text{adv}} \sim 2500 \, \text{km s}^{-1}; \) see Persic & Rephaeli 2010, from Eq.(13) we get \( U_p \sim 95 \, \text{eV cm}^{-3} \) (SN method).

NGC 253. Following Rephaeli et al. (2010; and refs. therein) we assume \( r_s = 200 \, \text{pc}, \) \( f_{1 \, \text{GHz}} = 5.6 \, \text{Jy}, \) and \( \alpha = 0.75. \) The latter implies \( q \approx 2.50, \) hence \( a = 0.0852 \) and \( \kappa \approx 8. \) From Eq.(8) we obtain \( U_p \sim 63 \, \text{eV cm}^{-3} \) in the starburst nucleus (radio method). Being \( \nu_{SN} = 0.12 \, \text{yr}^{-1} \) and \( \tau_{\text{res}} \sim \tau_{\text{adv}} \sim 3 \times 10^4 \, \text{yr} \) (being \( n_p \sim 10^2 \, \text{km s}^{-1} \) in the starburst nucleus, and \( v_{\text{adv}} \sim 2500 \, \text{km s}^{-1}; \) see Persic & Rephaeli 2010, we get \( U_p \sim 75 \, \text{eV cm}^{-3} \) (SN method).

Milky Way. Measurements of Galactic CRs indicate \( U_p \approx 1 \, \text{eV} \) at the Sun’s position. The Galactic CRp flux measured locally is the result of the superposition of particles, accelerated in several sites scattered throughout the Galaxy, that have diffused out into the disk. By this argument, if we consider the whole Galaxy as a site of SN explosions, i.e. we use a radius of 15 kpc and a thickness of 0.5 kpc, then in Eq.(13) we use \( r_s = 4.4 \, \text{kpc}, \) \( \tau_{\text{res}} \sim 2 \times 10^7 \, \text{yr} \) (being \( n_p \sim 1 \, \text{cm}^{-3} \), and \( \nu_{SN} = 0.02 \, \text{yr}^{-1} \) and obtain \( U_p \sim 1 \, \text{eV cm}^{-3} \) (SN method). In order to compare the SN-based estimate to available measurements of the innermost Galactic region, Persic & Rephaeli (2010) estimated \( U_p \sim 5 \, \text{eV cm}^{-3} \) in the central \( r_s = 0.2 \, \text{kpc} \) (SN method).
From Beck & Gräve (1982) we derive a nonthermal radio flux $f_{1 \text{GHz}} = 4.8 \text{ Jy}$ and $\alpha = 0.88$ averaged over 19.2 kpc radius. The latter corresponds to $\sim 3.34$ exponential length scales ($R_d = 5.75 \text{ kpc}$), i.e. it encompasses $\sim 85\%$ of the mass of the corresponding exponential disk, hence most of the stellar distribution: for an assumed thickness of 0.5 kpc, we get $r_s = 5.17 \text{ kpc}$. The measured spectral radio index implies $q = 2.76$, that in turn implies $a \simeq 0.08$ and $\kappa \simeq 4$. From Eq.(8) we obtain $U_p \simeq 0.9 \text{ eV cm}^{-3}$ (radio method). Taking the whole disk as a site for SN explosions, the implied average gas density is $n_p \approx 0.5 \text{ cm}^{-3}$, hence $\tau_{\text{res}} \sim \tau_{\text{pp}} \approx 3.7 \times 10^5 \text{ yr}$. From Eq.(13) we derive $U_p \approx 0.2 \text{ eV cm}^{-3}$ (SN method).

**M 31.** From this galaxy star formation proceeds scattered along the spiral arms. So we consider the whole disk as the site of SN explosions and of CR acceleration. From Tabatabaei et al. (2007) we derive a nonthermal radio flux characterized by and $f_{1 \text{GHz}} = 3.3 \text{ Jy}$ and $\alpha = 0.95$ averaged over 7.6 kpc radius. The latter corresponds to 5.3 exponential length scales ($R_d \simeq 1.43 \text{ kpc}$), i.e. it encompass 97% of the mass of an exponential disk, hence virtually the whole stellar distribution: for an assumed thickness of 0.5 kpc, we get $r_s = 2.79 \text{ kpc}$. The measured spectral radio index implies $q = 2.90$, that in turn implies $a \simeq 0.08$ and $\kappa \simeq 3$. From Eq.(8) we obtain $U_p \simeq 0.8 \text{ eV cm}^{-3}$ (radio method). Given the gas mass reported in Table 1, the average gas density is $n_p \sim 1 \text{ cm}^{-3}$, hence $\tau_{\text{res}} \sim \tau_{\text{pp}} \sim 2 \times 10^7 \text{ yr}$. Inserting the relevant quantities (see Table 1) into Eq.(13), we then derive $U_p \sim 0.7 \text{ eV cm}^{-3}$ (SN method).

**LMC.** This satellite of the Milky Way can be modeled as a truncated disk/spheroid with $r_1 \simeq 3 \text{ kpc}$ whose half-thickness is also $\sim 3$ kpc (Weinberg & Nikolaev 2001), so we use $r_s = 3 \text{ kpc}$ in Eqs.(13,8). The measured spectral radio index implies $q = 2.68$, that in turn implies $a \simeq 0.08$ and $\kappa \simeq 5$. Eq.(8) yields $U_p \simeq 0.1 \text{ eV cm}^{-3}$ (radio method). There is no mass outflow in the LMC, hence $\tau_{\text{res}} \sim \tau_{\text{pp}} \approx 10^6 \text{ yr}$. (The average gas density is $n_p \approx 2 \text{ cm}^{-3}$.) Eq.(13) then yields $U_p \approx 0.2 \text{ eV cm}^{-3}$ (SN method).

**SMC.** This other Milky Way satellite can be modeled as a bar with sizes $\sim 2.5 \times 1.5 \text{ kpc}$ (Wilke et al. 2003) with a l.o.s. depth of 4 kpc (following Abdo et al. 2010d), so we use $r_s = 1.53 \text{ kpc}$ in Eqs.(13,8). The measured spectral radio index implies $q = 2.70$, that in turn implies $a \simeq 0.08$ and $\kappa \simeq 4$. From Eq.(8) we obtain $U_p \sim 0.10 \text{ eV cm}^{-3}$ (radio method). The SMC has a (galaxy-wide) SN rate of $\nu_{\text{SN}} = 10^{-5} \text{ yr}^{-1}$. There is no mass outflow from the SMC, so $\tau_{\text{res}} \sim \tau_{\text{pp}} \sim 1.4 \times 10^5 \text{ yr}$. (It is $n_p \approx 1.4 \text{ cm}^{-3}$.) From Eq.(13) we then obtain $U_p \approx 1 \text{ eV cm}^{-3}$ (SN method).

The $U_p$ values estimated according to the various methods are reported in Table 2. They are only as precise as the quantities used to estimate them can be (see Persic & Rephaeli 2010 for a more complete discussion). Measuring $\nu_{\text{SN}}$ may be strongly affected by heavy optical extinction (e.g., in starburst nuclei), and radio counts of SN remnants need information on their ages in order to be turned into actual SN rates: for our sample galaxies, published observational results suggest that $\nu_{\text{SN}}$ are known to within a factor of $\lesssim 1.5$. The main uncertainty in the value of $\tau_{\text{res}}$ arises from the fast wind velocity, that is probably known to within $\sim 50\%$. For the energy released by a core-collapse SN that is available for CR acceleration, we have assumed the ‘Milky Way normalization’ (i.e., $5\%$ of $10^{51} \text{ erg per SN}$) to hold also for the galaxies in Table 1. For the starburst galaxies considered in Table 1, the starburst radii $r_s$ are deduced from high-resolution optical and radio data, so their values are quite accurate. We conclude that the galaxy quantities in Table 1 relevant to Eq.(13) are quoted in the literature as observationally precise, to within a factor of $\lesssim 2$.

**6. Discussion**

The three methods discussed here are not independent. The $\gamma$-ray method and the radio method are coupled through the $p/e$ ratio at injection, through the secondary-to-primary electron ratio (which in turn depends on the fraction of CRs that interact with the ambient matter during their residency time in the emission region), and through the imposed condition of particle-field
Table 2. Star-forming galaxies: CRp energy densities$^+$.  

| Object   | $\gamma$-ray meth. | radio meth. | SN meth. | other meth. | $r_s$ (kpc) | mode |
|----------|-------------------|-------------|----------|-------------|-------------|------|
| Arp 220  | –                 | 615         | 515      | –           | 0.25        | adv  |
| M 82     | 200$^{a,c}$       | 90          | 95       | –           | 0.26        | adv  |
| NGC 253  | 200$^{b,c}$       | 63          | 77       | –           | 0.20        | adv  |
| Milky Way| $1^d$             | –           | 1        | $1^i$       | 4.4         | pp   |
|          | $6^e$             | –           | 5        |             | 0.2         | pp   |
| M 31     | 0.36$^f$          | 0.9         | 0.7      | –           | 4.77        | pp   |
| M 33     | $<3^f$            | 0.8         | 0.7      | –           | 2.79        | pp   |
| LMC      | 0.25$^g$          | 0.1         | 0.2      | –           | 3           | pp   |
| SMC      | 0.15$^h$          | 0.1         | 1.0      | –           | 1.53        | pp   |

$^+$ Values are in eV cm$^{-3}$.

(a) Acciari et al. 2009 (see also Persic et al. 2008 and De Cea et al. 2009). (b) Acero et al. 2009 (see also Paglione et al. 1996, Domingo-Santamaría & Torres 2005, and Rephaeli et al. 2010). (c) Abdo et al. 2010a. (d) Strong et al. 2010. (e) Aharonian et al. 2006. (f) Abdo et al. 2010b, with Drury et al. 1994 in the case of M 33. (g) Abdo et al. 2010c. (h) Abdo et al. 2010d. (i) Webber 1987.

equipartition. The SN method is not independent of the $\gamma$-ray method either, because they both depend on the residency time of CRp in the emission region - although, unlike the $\gamma$-ray and radio methods, it does not depend on the particles’ radiative yields but on the statistics of core-collapse SN. Also, the thee methods are not on equal footing: the $\gamma$-ray, radio, and SN method respectively measure, infer, and estimate the value of $U_p$. This, because: (i) $\pi^0$-decay $\gamma$-ray emission is the most robust measure of $U_p$ once the distribution of target gas is known and the particles’ diffusion and losses are treated accurately and self-consistently (like in published numerical models of M 82 and NGC 253); whereas (ii) radio emission enables deduction of $U_p$ from electron synchrotron flux and spectrum once assumptions have been made on the link between energetic electrons and protons, and between such particles and the magnetic field; and (iii) assuming a SN origin for CRs, SN statistics for a given (region of a) galaxy leads to an estimate of $U_p$ there.

A substantial agreement among estimates based on the three methods is reached for most of the galaxies in Table 1. The only exception is the SMC, whose CR confinement volume could be small, so that most CRs diffuse out and get lost to the intergalactic space (Abdo et al. 2010d). If so, the $\gamma$-ray method returns the (lower) actual CRp energy density whereas the radio and SN methods estimate the (higher) produced amount.

Once these considerations are weighed in, the discrepancy between the very high CRp energy densities ($U_p \sim \mathcal{O}(10^2)$ eV cm$^{-3}$) deduced for starburst nuclei and the low values ($U_p \sim \mathcal{O}(10^{-1})$ eV cm$^{-3}$) deduced for very quiet environments appears very significant. Also, our sample galaxies do conform to the notion of a SN-powered VHE $\gamma$-ray luminosity.

7. Conclusions
Using 8 galaxies for which pointed GeV-TeV data (from Fermi/LAT and from Cherenkov telescopes) are available, we have estimated $U_p$ using the radio, $\gamma$-ray, and SN methods. A
substantial agreement among estimates based on the three methods is reached for 9 galactic regions (3 starburst nuclei, the Milky Way’s disk and central region, 4 quiescent galaxies) considered in this paper. The discrepancy between the very high values \( U_p \sim O(10^2) \text{eV cm}^{-3} \) found in starburst nuclei like M82 and NGC 253, and the low values \( U_p \sim O(10^{-1}) \text{eV cm}^{-3} \) found in very quiet environments like the Local Group galaxies, appears to be highly significant.

Based on the results of this study, we confirm and extend our earlier suggestions: (i) star-forming galaxies are effective CR accelerators; (ii) CRp energy densities in star-forming galaxies range from \( O(10^2) \text{eV cm}^{-3} \) in very active environments down to \( O(10^{-1}) \text{eV cm}^{-3} \) in very quiet ones; (iii) equipartition CR and magnetic field energy densities can be used as proxies of the actual quantities; and (iv) core-collapse SNe share a universal CR acceleration efficiency. An expanded version of this paper (Persic & Rephaeli 2011) is underway.

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