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# Normal Galaxies as Sources of Cosmic Rays, Photons and Neutrinos

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In this contribution we estimate the luminosity in Cosmic Rays, high energy photons and neutrinos of our Galaxy, extrapolate the calculation to other galaxies, and integrating the emission over time calculate the contribution of "normal galaxies" to the extragalactic diffuse fluxes of Cosmic Rays, photons and neutrinos. We compare these results to the existing data and to the contributions of other possible sources.

## 1. Introduction

There is clear evidence that most of the cosmic rays observed near the Earth are of galactic origin, that is they are produced in our Galaxy and remain confined (because of the galactic magnetic fields) for a rigidity dependent time, while the cosmic ray density in intergalactic space is significantly smaller. The extra-galactic cosmic ray component is only measurable at very high energy, when it becomes larger than the softer galactic component. The determination of the energy $E^*$ at which the galactic and extra-galactic components are equal is one of the most important goals of cosmic ray research and will require precise observations of the c.r. energy spectrum, composition and angular anisotropy. It has been often assumed $E^*$ corresponds to the "ankle" energy (at $E \simeq 10^{19}$ eV), however it is also argued that the crossing energy $E^*$ is lower, and can perhaps be associated with the so called "second knee".

Our own Galaxy is a source of cosmic rays, since most particles above $E_{\min} \sim 5\ Z$ GeV escape from the confinement volume with only a negligible energy loss, similarly we do expect that all galaxies are cosmic ray sources and a natural problem is the estimate the contribution of the ensemble of all galaxies to the extragalactic density of cosmic rays. It is possible that this "normal galaxies" contribution can naturally reproduce the observed flux of the extragalactic component. Alternatively most of the observed (extragalactic) UHE cosmic rays could be produced in a different class of accelerators such as Active Galactic Nuclei. More in general it could be that several classes of sources for CR acceleration give significant contributions to the extra-galactic CR population, and one one will need to identify and disentangle these components.

The ensamble of the extra-galactic cosmic ray accelerators are also likely to be (after galactic emission) the largest source of high energy astrophysical neutrinos, since for each accelerated particle a number $f(E)$ will interact inside (or in the vicinity of the accelerator) generating neutrinos and photons. A precise estimate clearly depends on the identification and correct description of the cr accelerators.

## 2. Extra-Galactic Cosmic Rays

The production of extra-galactic cosmic rays is characterized by the injection rate $Q_{\rm cr}(E,z)\ dE$ (number of particles injected per unit time and unit comoving volume at the epoch $z$). The present average density $n_{\rm cr}(E)$ of particles can then be calculated integrating over the cosmic injection history and taking into account the energy loss mechanisms:

$$n_{\rm cr}(E) = \int dz \ \left|\frac{dt}{dz}\right| \int dE_0 \ Q_{\rm cr}(E_0, z)\, P(E; E_0, z) \qquad (1)$$

where $dt/dz = -[H(z)(1+z)]^{-1}$ (the Hubble constant depends on the cosmological parameters: $H(z) = H_0 [\Omega_m (1+z)^3 + \Omega_\Lambda + (1-\Omega_m-\Omega_\Lambda)(1+z)^2]^{1/2}$) and $P(E; E_0, z)$ is the probability that a particle injected at redhshift $z$ with energy $E_0$ will survive with energy $E$ at the present epoch. Neglecting interactions (that is a good approximation for c.r. below $10^{18}$ eV) the only significant source of energy loss is the cosmological redshift and one can approximate the probability as: $P(E; E_0, z) = \delta\,[E - E_0/(1+z)]$. In general the space distribution of extra-galactic cosmic rays could exhibit dishomegeneities if the extra-galactic magnetic fields are sufficiently strong, however equation (1) remains valid after averaging over an appropriate length scale. The energy density in cosmic rays that corresponds to (1) can be expressed as:

$$\rho_{\rm cr} = \int dz \left|\frac{dt}{dz}\right| \frac{\mathcal{L}_{\rm cr}(z)}{(1+z)} = \frac{\mathcal{L}^0_{\rm cr}}{H_0}\,\xi \qquad (2)$$

where $\mathcal{L}_{\rm cr}(z) = \mathcal{L}^0_{\rm cr}\, G(z)$ is the c.r. power density at epoch $z$ (with $G(z)$ describing the cosmic evolution of the comoving volume source density). The constant $\xi$ is a pure number of order unity that depends on the cosmic evolution of the sources via the function and the cosmological parameters. For a constant injection rate and a flat, matter dominated universe ($\Omega_m = 1$, $\Omega_\Lambda = 0$) one has $\xi = 2/5$; for the "best fit" cosmological parameters: ($\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$), and a constant injection rate one obtains $\xi \simeq 0.532$, that is 30% higher. The factor $\xi$ depends more strongly on the function $G(z)$ that describes the cosmic history of the injection. A reasonable assumption is that the particle injection rate is correlated to the injection rate of stellar light ($\mathcal{L}_{\rm cr} \propto \mathcal{L}_{\rm star}$). Studies of the time dependence of the star-light emission show that in the past this emission was more intense For an explicit form of $G(z)$ we have used the redshift dependence of star formation as calculated in [1]. Using this form for $G(z)$ the factor $\xi$ in (2) becomes $\xi \simeq 1.35$ for $\{\Omega_m, \Omega_\Lambda\} = \{1,0\}$ and $\xi \simeq 2.07$ for $\{0.3,0.7\}$. The shape of the energy distribution of the particle density $N(E)$, reflects the shape of the spectrum of injection density, with small distortions due to the redshift effects. In case of an injection that is a power law in energy:

$$Q_{\rm cr}(E,z) = Q^0_{\rm cr}\, G(z)\, E^{-\alpha} \qquad (3)$$

the particle density at the present epoch is also a power law with the same index. In fact inserting the injection density (3) in equation (1) one obtains $\phi_{\rm cr}(E) \equiv c/(4\pi)\, n_{\rm cr}(E) = K\, E^{-\alpha}$ . For $\alpha = 2$ and assuming that the particle injection is between limits $E_{\rm min}$ and $E_{\rm max}$, one has:

$$K = \frac{c}{4\pi}\frac{\mathcal{L}^0_{\rm cr}}{H_0}\frac{\xi}{\ln(E_{\rm max}/E_{\rm min})} \simeq 8.6\times 10^{-11} \left[\frac{\mathcal{L}_0}{(L_\odot/{\rm Mpc}^3)}\right] \frac{\xi}{\ln(E_{\rm max}/E_{\rm min})} \left(\frac{\rm GeV}{\rm cm^2\, s\, sr}\right) \qquad (4)$$

For $K = 10^{-8}$ GeV/cm$^2$, one obtains an injection power: $\mathcal{L}^0_{\rm cr}\,\xi = 116 \ln(E_{\rm max}/E_{\rm min})\, L_\odot\, {\rm Mpc}^{-3}$. For comparison, the largest contribution to the average energy density in the universe ( after the microwave background radiation, with an integrated energy density $\rho_{\rm CMBR} \simeq 0.26$ eV/cm$^3$) is the stellar light emission (and reprocessing by dust absorption and re-emission) that has an energy density star 0.026 eV/cm$^3$, with an estimated allowed interval 0.013-0.044 eV/cm$^3$ [2]. Using equation (2) this corresponds to:
$\mathcal{L}^0_{\rm cr}\,\xi = (0.36 \div 1.23) \times 10^9\, L_\odot\, {\rm Mpc}^{-3}$

## 3. Galactic Cosmic Rays

Our Galaxy contains a population of c.r. in an approximately stationary time, that is constantly replenished with an input power of order $L^{\rm Gal}_{\rm cr} \simeq 10^{41}$ erg/s. The lowest rigidity particles, because of their very long galactic confinement time have a non negligible probability to interact with the ISM, however for rigidity larger than few GeV, most of the CR escape the Galaxy without losing significant amounts if energy. In first

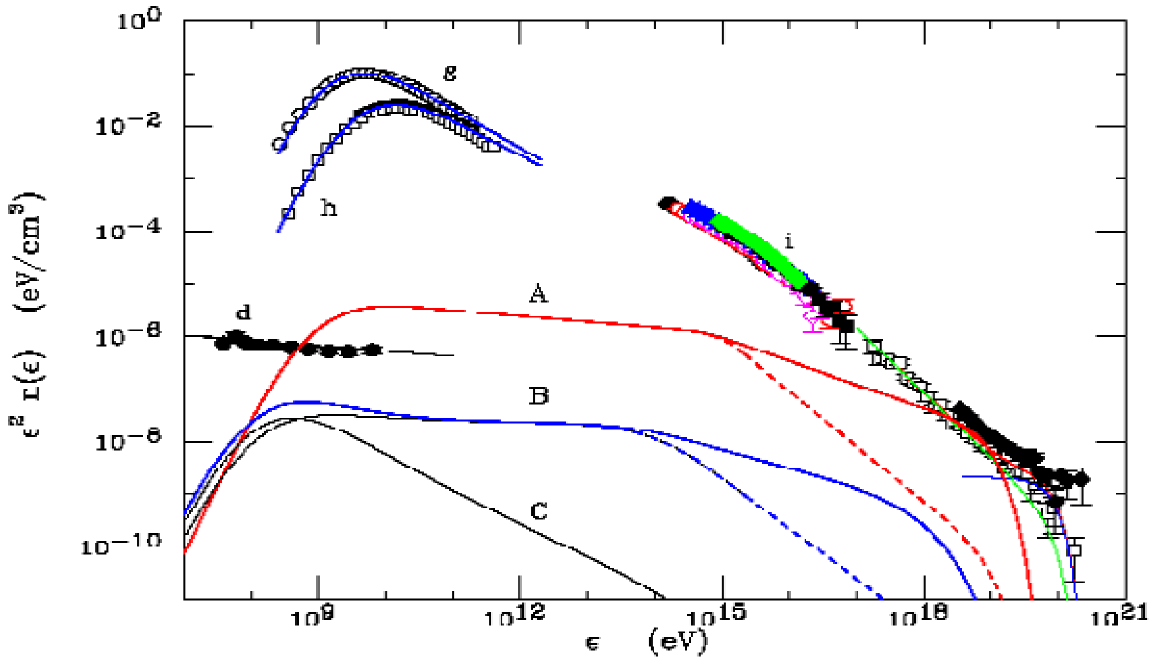


**Figure 1**. Curve (A) shows the estimated average density of extra-galactic cosmic rays from the emission of normal galaxy. Curve (C) shows the estimated average extragalactic density of photons generated by CR confined in normal galaxies that interact with the local interstellar medium. Curve (B) gives the average density of extragalactic photons emitted by CR interactions, near their accelerators, assuming that the CR cross an energy independent column density of 3 g cm$^{-2}$ leaving the accelerator. The high energy behaviour of curves (A) and (B) has two forms (described by the solid and dashed lines), because of two different assumption about CR injection in our Galaxy (see text).

approximation[3] the time evolution of the CR population in the Galaxy can be described assuming a stationary state as:

$$0 = \frac{\partial N_{\rm cr}^{\rm Gal}(E)}{\partial t} = Q_{\rm cr}^{\rm Gal}(E) - \frac{N_{\rm cr}^{\rm Gal}(E)}{\tau_{\rm esc}(E)} - \frac{N_{\rm cr}^{\rm Gal}(E)}{\tau_{\rm int}(E)} \tag{5}$$

where $N_{\rm cr}^{\rm Gal}(E) = n_{\rm cr}^{\odot}(E)\, V_{\rm Gal}^{\rm eff}$ is the CR population in the Galaxy ($n_{\rm cr}^{\odot}(E) = 4\pi/c\ \phi_{\rm cr}^{\odot}(E)$ is the CR density in the vicinity of the solar system) and $V_{Gal}$ is the c.r. effective confinement volume), and the three terms on the right-hand side of the equation are one source term due to the galactic accelerators, and two sink contributions due to interactions and escape from the Galaxy. The solution of (5) is:

$$N_{\rm cr}^{\rm Gal}(E) = Q_{\rm cr}^{\rm Gal}(E)\, \frac{\tau_{\rm int}\ \tau_{\rm esc}}{\tau_{\rm int} + \tau_{\rm esc}} \tag{6}$$

This implies that the Galaxy is emitting c.r. at a rate:

$$Q_{\rm cr(out)}^{\rm Gal}(E) = \frac{N_{\rm cr}^{\rm Gal}(E)}{\tau_{\rm esc}(E)} = Q_{\rm cr}^{\rm Gal}(E)\ \frac{1}{1 + \tau_{\rm esc}(E)/\tau_{\rm int}(E)} \tag{7}$$

The interaction time for protons is

$$\tau_{\rm int} \simeq (c\,\sigma_{pp}(E)\ \langle n_{\rm ism}\rangle)^{-1} \simeq 1.1\times 10^{8}\ [\sigma_{pp}/(30\ {\rm mbarn})]^{-1}\ [\langle n_{\rm ism}\rangle/(0.3\ {\rm cm}^{-3})]^{-1}\ {\rm years} \tag{8}$$

and varies slowly with energy. A critical problem is the estimate of the confinement time esc(E). For this purpose we can use the results of the HEAO-3 satellite [4], where the results on the energy spectrum secondaries nuclei (like Li,Be,B) that are abundant in CR, since they are produced by the spallation of heavier nuclei(like Carbon or Oxygen), are interpreted fitting the column density(for rigidity $R > 4.4$ GV as: $\lambda_{\rm esc}(R) = 34.1\beta\ R^{-0.60}$g cm$^{-2}$, or (using $\lambda = c\tau\ \langle \rho_{\rm ism}\rangle)\ \tau_{\rm esc}(E) = 7.2 \times 10^7\ \left[\langle n_{\rm ism}\rangle/(0.3\ {\rm cm}^{-3})\right]^{-1}\ R^{-0.6}$ years. These results are consistent with measurements of unstable nuclei like $^{10}$Be [5]. It is remarkable that from these results one obtains that the injection of CR inside the Galaxy has the form $Q_{\rm cr}(E)\ \alpha\ E^{-2.1}$ that is approximately what is expected from 1st order Fermi acceleration at a shock. It should however noticed that a rigidity dependence $\alpha\ R^{-0.67}$ becomes of difficult interpretation for large $R$. In fact for rigidity $R \simeq 1.2 \times 10^6$ GV, the predicted escape length becomes 5 Kpc, that is of order of the size of the Galaxy. For this reason we have calculate the emission of CR from our Galaxy using for $\tau_{esc}$ the simple form) $\tau_{esc} \propto E^{-0.6}$ with a power law that extends with the same slope up to very high energy, and we have repeated the calculation with $\tau_{esc}$ that becomes a constant for $R > 1.1 \times 10^6$ GV. To compute the injection of cr from the ensamble of all galaxies the simplest assumption is to relate the cr injection to the starlight emission:

$$Q_{\rm cr}(E, z) = Q^{\rm Gal}_{\rm cr(out)}(E)\ [\mathcal{L}_{\rm star}(z)\ /\ L_{\rm Gal}] \tag{9}$$

where $L_{\rm Gal} \simeq 3\times 10^{10} L_\odot$ is the bolometric luminosity of our Galaxy [6], and for the star-light power density we have used $\mathcal{L}_{\rm star}(z) = 0.35 \times 10^9\ G_{\rm star}(z)\ L_\odot/{\rm Mpc}^3.$ with $G_{\rm star}(z)$ the cosmic evolution of [1].

The calculation of the spectrum of cr generated by normal galaxies is shown as curve A in fig. 1. The solid (dashed) curve is calculated assuming at high energy $\tau_{esc}(E) \propto E^{-0.6}$ ( $\tau_{esc}$ =const).

### 3.1 Photons and Neutrinos

The production of cosmic rays is unavoidably associated with the production of photons and neutrinos created in the decay of the pions produced in interactions inside or near the accelerators. Additional photons and neutrinos at very high energy are produced during the propagation of c.r. in particular because of interactions with the CMBR. For example one can associate a neutrino injection $Q_\upsilon(E_\upsilon, z)$ to the C.R. injection $Q_{\rm cr}(E_0, z)$ as:

$$Q_\nu(E_\nu, z) = \int dE_0\, Q_{\rm cr}(E_0, z) \times f(E_0) \times \frac{dn_\nu}{dE_\nu}(E_\nu; E_0) \tag{10}$$

where $dn_\upsilon/dE_\upsilon\ (E_\upsilon; E_0)$ is the number of neutrinos of energy $E_\upsilon$ produced in the interaction of a primary particle of energy $E_0$ and the factor $f$ gives the number of interactions per injected particle. In general the factor $f$ will be a function of the energy $E_0$ and (for a non trivial evolution of the sources) possibly also a function of z. If one makes the assumption that $f < 1$ (thin sources) one can deduce an upper limit [7] for the neutrino flux from an estimate of the extragalactic cosmic ray flux. The photon diffuse flux from the model In the case of the standard galactic sources, considering the entire galaxy as the accelerators one can an estimate $f(E_0) \sim c\,\tau_{\rm esc}\,\langle n_{\rm ism}\rangle$ falls steeply with energy (curve C in fig. 1). An additional contribution due to interactions in the dense material of the individual sources results in the curve(s) B in fig. 1.

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