WHAT IS THE COSMIC-RAY LUMINOSITY OF OUR GALAXY?

Arnon Dar
Technion, Israel Institute of Technology, Haifa, Israel
and
Theoretical Physics Division, CERN
CH - 1211 Geneva 23

and

A. De Rújula
Theoretical Physics Division, CERN
CH - 1211 Geneva 23

ABSTRACT

The total cosmic-ray luminosity of the Galaxy is an important constraint on models of cosmic-ray generation. The diffuse high energy $\gamma$-ray and radio-synchrotron emissions of the Milky Way are used to derive this luminosity. The result is almost two orders of magnitude larger than the standard estimate, based on the observed isotopic abundances of cosmic ray nuclides. We discuss the plausible interpretation of this discrepancy and the possible origin of such a relatively large luminosity.
Almost a century after they were discovered, our understanding of cosmic rays is still very limited. Their production mechanisms, composition and energy spectrum continue to be debatable. In this letter we discuss the total cosmic ray (CR) luminosity of our Galaxy, a crucial constraint on models of galactic CR generation.

The CR nuclei have a power-law spectral flux \( \frac{dF}{dE} \propto E^{-\beta} \) with a series of break-point energies: \( \beta_{1,2,3} \sim 2.7, 3.0, \) and \( 2.5 \) in the intervals \( 10 \text{ GeV} < E < E_{\text{knee}} \sim 3 \times 10^6 \) GeV, \( E_{\text{knee}} < E < E_{\text{ankle}} \sim 3 \times 10^9 \) GeV, and \( E_{\text{ankle}} < E < 3 \times 10^{11} \) GeV. Below \( E_{\text{knee}} \), protons constitute \( \sim 96\% \) of the CRs at fixed energy per nucleon. Their flux and number density above \( E_p \sim 10 \text{ GeV} \) is (see, for instance, Wiebel-Sooth and Biermann 1998 and references therein):

\[
\frac{dF_p}{dE} \simeq 1.8 \left[ \frac{E}{\text{GeV}} \right]^{-2.70 \pm 0.05} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ GeV}^{-1}.
\]  

(1)

The spectral indices of heavier nuclei are compatible within errors with that of protons and, given the dominant abundance of the latter, we need not distinguish here between CR protons and the ensemble of nuclear CRs. It is generally believed that the bulk of the CR nuclei with energy below the knee are Galactic in origin, and that their main production mechanism is acceleration by supernova shocks (see, for instance, Ginzburg and Syrovatskii 1964; Longair 1981; Berezinskii et al. 1990; Gaiser 1990).

If the CRs are chiefly Galactic in origin, their accelerators must compensate for the escape of CRs from the Galaxy, in order to sustain the observed Galactic CR intensity: it is known from meteorite records that the CR flux has been steady for the past few giga-years (Longair 1981). The Milky Way’s luminosity in CRs must therefore satisfy:

\[
L_{\text{CR}} \simeq L_p = \frac{4\pi}{c} \int \frac{1}{\tau_{\text{conf}}} E \frac{dF_p}{dE} dE dV,
\]

(2)

where \( \tau_{\text{conf}}(E) \) is the mean confinement time in the Galaxy of CRs of energy \( E \).

The standard estimate of \( L_{\text{CR}} \) runs along the following lines. The mean column density \( X \) traversed by CRs before they reach the Earth can be extracted from the observed ratios of primary to secondary CRs. The result is \( X \approx 6.9 \left[ \frac{E(\text{GeV})}{(20 Z)} \right]^{-0.5} \text{ g cm}^{-2} \) (Swordy et al. 1990). With use of \( X = \int \rho \, dx \sim \bar{\rho} c \tau_{\text{conf}} \) one can extract the product of \( \tau_{\text{conf}}(E) \).
and a path-averaged density $\bar{\rho}$. Assume the locally measured values of $X$ and $\frac{dF_p}{dE}$ to be representative of the Galactic values dominating the integral in Eq. (2), to obtain:

$$L_{CR} \sim \frac{4\pi}{c} \int \bar{\rho} dV \int \frac{1}{X} E \frac{dF_p}{dE} dE .$$

(3)

Assume the path-averaged $\bar{\rho}$ to be close to the average density $\rho$ of neutral and ionized gas in the Galaxy, so that $\int \bar{\rho} dV$ is the total mass of Galactic gas, estimated from X-ray, optical and radio observations (Longair 1981) to be $M_{gas} \approx 4.8 \times 10^9 M_\odot$. The integration over energy is not unduly sensitive to its lower limit and converges rapidly above the knee. The final result (Drury et al. 1989) is:

$$L_{CR} \sim 1.5 \times 10^{41} \text{ erg s}^{-1} .$$

(4)

Earlier estimates (e.g. Berezinskii et al. 1990 and references therein) of $L_{CR}$, which used the “Leaky Box” model of CR confinement, led to somewhat smaller luminosities.

In spite of the cursory character of the above luminosity estimate, Eq. (4) is consistent with the assumption that CRs are dominantly accelerated by the turbulent magnetic fields of supernova (SN) remnants, generated by the expansion of the debris from the SN explosion into the interstellar medium. For an estimated mean Galactic rate of one supernova every $\sim 50$ years (van den Bergh and Tammann 1991) and an average kinetic energy $\langle E_k \rangle \approx 10^{51}$ erg of the debris, this explanation requires an $\epsilon \sim 20\%$ efficiency in the conversion of kinetic energy into CRs.

The model of CR generation by SNe is incomplete or problematic in several respects (e.g. Plaga et al. 1999). Supernova-generated shocks are not sufficiently lasting and energetic to produce CRs with energies well above $E_{knee}$ (e.g. Lagage and Cesarsky 1983). The space distribution of SNe is too concentrated in the Galactic disk and bulge to give a proper description of the relative isotopic abundances of CRs, in particular $^{10}\text{Be}/^{9}\text{Be}$ (Strong and Moskalenko 1988), of the directional distribution of the diffuse $\gamma$-ray background radiation (Strong and Mattox, 1996) and of the high energy $\gamma$-rays produced by CR interactions in the interstellar medium (Strong and Moskalenko 1998). The CR luminosity of SN remnants is severely constrained by TeV $\gamma$-ray observations and
results in a CR-generation efficiency $\epsilon$ between 1 and 5% (Allen et al. 1999), somewhat short of the required $\epsilon \sim 20\%$.

In this letter we present an alternative estimate of the luminosity of CR nuclei, based on the Galactic CR-electron luminosity, which we infer from observations of $\gamma$-ray production (Hunter et al. 1997; Sreekumar et al. 1998) and synchrotron emission (e.g. Chen et al. 1996) by CR electrons.

The EGRET detector on the Compton GRO satellite has mapped the intensity and spectral index of the “diffuse” $\gamma$-ray background (GBR) above $E_\gamma = 30$ MeV, at latitudes above the Galactic disk and bulge. The observed spectrum, $dF/dE_\gamma \propto E^{-\beta_\gamma}$, has an index $\beta_\gamma \simeq 2.10 \pm 0.03$ that is independent of direction. The intensity is also roughly isotropic, thus the claim of a dominantly extragalactic origin of the GBR.

We have recently shown (Dar and De Rújula, 2000) that the GBR intensity is significantly correlated with the angle away from the galactic centre and that it is dominated at high latitudes by inverse Compton scattering (ICS) of CR electrons from the cosmic microwave background radiation (CBR) and from starlight, obviating the recourse to unspecified extragalactic sources (the importance of ICS has also been stressed in, Strong and Moskalenko 1998; Strong et al. 2000). Earlier evidence for a large galactic contribution to the GBR at large latitudes had been found by Chen et al. (1996), who discovered a strong correlation between the observed EGRET GBR $\gamma$-ray intensity and the galactic radio continuum emission at 408 MHz, which is dominated by synchrotron radiation from the very same CR electrons that produce $\sim 100$ MeV $\gamma$-rays by ICS from galactic stellar light.

Our model of the origin of the GBR is based on the assumption that the average Galactic CR-electron spectrum has the same energy dependence as the locally observed one (for a recent compilation of experimental results see Wiebel-Sooth and Biermann 1998). This spectrum is well fit, from $\sim 10$ GeV to $\sim 2$ TeV, by:

$$\frac{dF_e}{dE} \simeq (2.5 \pm 0.5) \times 10^5 \left[ \frac{E}{\text{MeV}} \right]^{-3.2\pm0.10} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{MeV}^{-1}. \quad (5)$$
Starlight and CMB photons, upscattered by electrons with the spectral index of Eq. (5), have an energy dependence with index \( \beta_{\gamma} = (\beta_e + 1)/2 = 2.10 \pm 0.05 \), in perfect agreement with the observed direction-independent index of the GBR (Dar et al. 1999, Dar and De Rújula, 2000).

The relation between the spectral indices of CR protons and CR electrons in Eqs. (1) and (5) can also be understood in very simple terms. The confinement, residence or accumulation time of nuclear CRs in the Galaxy is \( \tau_{\text{conf}}(E) \propto X \propto E^{-0.5} \). The result must be of the same form for electrons, since relativistic particles of the same charge behave in the same way in a magnetic maze. The source spectrum of nuclear CRs, \( dF_p^s/dE \), is related to the observed spectrum of CR nuclei by \( dF_p/dE \propto \tau_{\text{conf}}(E) dF_p^s/dE \), so that the index of \( dF_p^s \) is \( \beta^s = \beta_p - 0.5 \approx 2.2 \). If the mechanism accelerating CR hadrons and CR electrons is the same e.g., first-order acceleration by a moving magnetic field (Fermi 1949, 1954) \( dF_p/dE \propto dF_e^s/dE \), and the source spectral index for electrons is also \( \beta^s \approx 2.2 \). Electrons, unlike nuclei, are significantly affected by ICS and synchrotron cooling—whose characteristic time is \( \tau_{\text{cool}} \propto m^2/E \)—so that, at sufficiently high energy, cooling takes over the accumulation-time effect in modulating the electron spectrum. The result (Dar et al. 1999, Dar and De Rújula, 2000) is \( \beta_e = \beta^s + 1 \approx 3.2 \), in agreement with Eq. (5).

In our study of the GBR we adopted, for the spatial distribution of the CR electron flux in the Galaxy, a model with a gaussian scale height \( h_e \) above the Galactic plane, and a scale radius \( \rho_e \) in directions perpendicular to the Galactic axis. By adjusting \( h_e \approx 20 \) kpc and \( \rho_e \approx 35 \) kpc, we reproduced the observed intensity and angular dependence of the GBR. We shall assume the nuclear CRs to be distributed as the CR electrons, with the ratio of fluxes fixed at its locally observed value. A scale height of CR nuclei \( h_{CR} = h_e \approx 20 \) kpc is larger than conventionally assumed, but is not excluded by data on relative CR abundances. For the most elaborate models (Strong and Moskalenko 1998) a “Leaky-Box” scale height of 20 kpc is only some 1.3 standard deviations below the central value of the most precise observations (Connell 1998) and is perfectly compatible with the average of all previous and somewhat less precise results, compiled in Lukasiak et al. (1994). Since our CR distribution is much more extensive than the visible part of the Galaxy, we refer
to it as the “cosmic-ray halo”.

The EGRET GBR data to which we fit the properties of a CR electron halo are gathered by masking the galactic plane at latitudes $|b| \leq 10^\circ$, as well as the galactic centre at $|b| \leq 30^\circ$ for longitudes $|l| \leq 40^\circ$. The volume of the CR halo is so much larger than that of the Galaxy within EGRET’s mask, that it is a very good approximation –in computing the Galaxy’s total CR luminosity– to use our halo model throughout the entire Galaxy (within the mask the model accounts for $\sim 1/2$ of the observed diffuse $\gamma$ radiation).

The successful relation between the spectral indices of the GBR and the CR electrons followed from the assumption that the production rate of CR electrons is equal to their cooling rate, which we estimate as follows. The starlight-photon density in the CR halo may be obtained by approximating our galaxy’s starlight as that produced by a source at its centre with the galactic luminosity $L_\star = 2.3 \times 10^{10} L_\odot \simeq 5.5 \times 10^{35}$ eV s$^{-1}$ (Pritchet and van den Bergh 1999): $n_\star \approx L_\star / (4 \pi c \epsilon_\star r^2)$, where $\epsilon_\star \sim 1$ eV is the average photon energy. For a gaussian CR halo, the mean $n_\star$ is given by:

$$\langle n_\star \rangle \approx \frac{L_\star}{4 \pi c \epsilon_\star \rho_e^2} \frac{1}{u} \ln \left( \frac{1+u}{1-u} \right) \approx 0.035 \text{ cm}^{-3},$$

(6)

with $u^2 = 1 - (\rho_e^2 / \rho_e^2)$. The mean energy density of starlight in the CR halo is much smaller than that of the CBR ($\sim 0.24$ eV cm$^{-3}$). If the local magnetic field-energy is in equipartition with the CR energy density, $B^2 / 8\pi \sim 1$ eV cm$^{-3}$, the mean total electromagnetic energy density in the halo is $\rho_\gamma \approx 1.27$ eV cm$^{-3}$. For the electron energy range of interest the Thomson limit of the $e\gamma$ cross section ($\sigma_T \approx 0.65 \times 10^{-24}$ cm$^2$) is accurate, even for ICS on starlight, and the mean cooling rate, $R_c$, of CR electrons by ICS and synchrotron radiation is (Dar and De Rújula 2000):

$$R_c(E) \equiv \frac{1}{\tau_{cool}(E)} \approx \frac{4 \rho_\gamma \sigma_T c E}{3 (m_e c^2)^2} \approx 4.0 \left( \frac{E}{\text{GeV}} \right) \text{ Gy}^{-1}.$$  

(7)

The luminosity of our galaxy in high energy electrons of energy above $E$, in equilibrium with their cooling rate by ICS and synchrotron radiation, is:

$$L_e(> E) \approx h_e \rho_e^2 \frac{4 \pi \frac{2}{3}}{c} \int dE E \frac{\partial}{\partial E} \left( R_c \frac{dF_e}{dE} \right).$$

(8)
By substituting the flux of Eq. (5), we obtain:

\[ L_e(> E) \approx 1.13 \times 10^{41} \left( \frac{h_e}{20 \text{ kpc}} \right) \left( \frac{\rho_e}{35 \text{ kpc}} \right)^2 \left( \frac{E}{2.5 \text{ GeV}} \right)^{-0.20 \pm 0.10} \text{ erg s}^{-1}. \]  

(9)

We have assumed that the ratio of the CR nuclear and electron fluxes is universal throughout the Galaxy. Thus, to estimate the Galaxy’s CR luminosity, it suffices to scale the electron luminosity \( L_e \) by the local ratio \( R \) of CR and electron fluxes. For the total fluxes, this ratio is \( R \sim 80 \). This result is uncertain, since it is dominated by CR-energies of \( \mathcal{O}(1) \) GeV, a domain in which the fluxes are affected by local magnetic and solar-wind effects. An independent estimate of \( R \) can be obtained as follows. The CR electron spectrum sharply steepens to an index \( \beta_e \approx 3.2 \) at \( E \sim 5 \) GeV: that must be the energy at which ICS and synchrotron radiation, for which \( \tau_{\text{cool}} \propto E^{-1} \), take over the effect of CR accumulation, for which \( \tau_{\text{conf}} \propto E^{-0.5} \) (the effects of local magnetic fields, the solar wind, Coulomb scattering, ionization losses and bremsstrahlung are only relevant at even lower energies). Thus, to within a factor of \( \mathcal{O}(2) \), the observed proton to electron flux ratio at \( E = 5 \) GeV must be the ratio of their source fluxes. We have argued that the source fluxes have the same spectral index. Thus, their ratio at fixed energy is also their energy-integrated ratio. This gives \( R \sim 60 \), in rough agreement with the previous estimate.

Multiply \( L_e \) in Eq. (9) by \( R = 60 \), to obtain:

\[ L_p(> E) \sim 6.8 \times 10^{42} \left( \frac{h_e}{20 \text{ kpc}} \right) \left( \frac{\rho_e}{35 \text{ kpc}} \right)^2 \left( \frac{E}{2.5 \text{ GeV}} \right)^{-0.20 \pm 0.10} \text{ erg s}^{-1}, \]  

(10)

which is almost two orders of magnitude larger than the estimate of Eq. (4).

If, as we argued, \( \tau_{\text{cool}} = \tau_{\text{conf}} \) at \( E \sim 5 \) GeV, we can use Eq. (7) to obtain \( \tau_{\text{conf}} = 250 \) Myr at \( E = 1 \) GeV. This is an order of magnitude larger than the values of \( \tau_{\text{conf}} \) obtained from the analysis of the relative abundances of unstable to stable CRs: \(^{10}\text{Be}/\text{Be} \) (Lukasiak et al. 1994; Connell 1998), \(^{26}\text{Al}/^{27}\text{Al} \) (Lukasiak et al. 1994b; Simpson and Connell 1998) and \(^{36}\text{Cl}/\text{Cl} \) (Connell et al. 1998). The discrepancy is even larger, since these data are for lower energies, of \( \mathcal{O}(250) \) MeV per nucleon. This alterity can be easily
understood (Plaga 1998). The confinement time is extracted from the isotopic ratios using a Leaky Box model, wherein the magnetic field of the Galaxy is confined to a region of dimensions similar to those of the visible part of the Galaxy. But, if the dense and luminous component of the Galaxy is embedded—as we surmise—in a much larger and less dense magnetized halo, the stable CRs may spend much of their travel time in the halo, while the unstable ones must have much shorter trajectories (the lifetimes of $^{10}$Be, $^{26}$Al, and $^{36}$Cl are a mere 1.6, 0.87, and 0.30 My, respectively). This is also the reason why our estimate of the CR luminosity, Eq. (10), is not truly contradictory to the much smaller conventional estimate of Eq. (4): the gas density, volume and grammage used to derive Eq. (4) all refer to CRs confined to a region close to the visible Galaxy.

What CR acceleration mechanism could give rise to the large luminosity of Eq. (10)? The bulk of the high energy CRs may be accelerated by relativistic jets emitted in the birth of neutron stars and stellar black holes in supernova explosions (Dar and Plaga 1999). If the mean sky velocity of neutron stars (Lyne and Lorimer, 1964), $\langle v_{ns} \rangle \approx 450 \pm 90 \text{ km s}^{-1}$, is due to an imbalance in this relativistic jet ejection, $E_{\text{jet}} > M_{ns} v_{ns} c \approx 4 \times 10^{51} \text{ erg}$, for $M_{ns} = 1.4 M_\odot$. If the kinetic energy of the jets is efficiently converted to CR energy, and for the estimated rate (van den Bergh and Tammann 1991) of Type II, Ib and Ic supernovae, $R_{\text{SN}} \sim 1/50$ per year, then:

$$L_{\text{CR}} \simeq 2 E_{\text{jet}} R_{\text{SN}} \approx 5.1 \times 10^{42} \text{ erg s}^{-1},$$

in reasonable agreement with Eq. (10).

Relativistic jets are emitted by active galactic nuclei and by galactic microquasars. These jets are observed to consist of “plasmoids” whose cross section, after an initial period of transverse expansion at the speed of sound in a relativistic plasma ($c/\sqrt{3}$), remains surprisingly constant until the jet sweeps enough material to stop and disperse as a blob (Rodriguez and Meribel 1999). If the plasmoids of the jets allegedly responsible for the peculiar velocities of neutron stars have a Lorentz factor $\gamma = E/M c^2$ of $\mathcal{O}(10^3)$, they are good candidate sources of $\gamma$-ray bursts (Dar and Plaga 1999). If the transverse size of these plasmoids of $\mathcal{O}(0.1) \text{ pc}$, the column density necessary to stop them is of the
same order as the one transverse to the galactic disk. Thus, the jets may reach the halo of the Galaxy before they stop, seeding it with a CR population and a magnetic field, and giving consistency to our overall picture.

REFERENCES


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