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On the viability of holistic cosmic-ray source models

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We consider the energy spectrum of cosmic-rays (CRs) from a purely phenomenological point of view and investigate the possibility that they are all produced by the same type of sources with a single power-law spectrum, in E^{-x}, from thermal to ultra-high energies. We show that the relative fluxes of the Galactic (GCR) and extra-galactic (EGCR) components are compatible with such a holistic model, provided that the index of the source spectrum be $x \simeq 2.31 \pm 0.07$. Interestingly, this is compatible with the best-fit indices for both GCRs and EGCRs, assuming that their source composition is the same, which is indeed the case in a holistic model. It is also compatible with theoretical expectations for particle acceleration at relativistic shocks and in gamma-ray burst.

1. Introduction

Despite considerable observational and theoretical progress over the last decades, the origin of cosmic-rays (CRs) remains a subject of intense debate. For historical and observational reasons, it is customary to distinguish between several regions in the CR spectrum. Some of these distinctions are artificial or related to the observational technique, while others have more phenomenological or theoretical grounds, in relation with observed or expected structures in the spectrum (e.g. due to solar modulation, energy losses, spatial diffusion, contributions of individual sources, loss of confinement, in-flight interactions with ambient material or radiation field...). However, despite the spectral features known as the *knees* and *ankle*, the most striking property of the CR spectrum is its overall regularity and coherence over (at least) 12 orders of magnitude in energy and 32 orders of magnitude in differential flux. This is quite extraordinary and unique for a non-thermal phenomenon. It is thus tempting to regard CRs as resulting from a universal astrophysical process and investigate the possibility that they are all produced by a single type of sources, from thermal energies up to a maximum energy, $E_{max} > 10^{20}$, that still remains to be determined. We refer to such a model as a *holistic model*.

Different versions have been proposed before, with gamma-ray bursts as the source of all CRs, notably within the cannonball model[1]. In [2], CRs below and above the knee are accelerated by the same astrophysical objects, but not by the same mechanism nor with the same spectrum. In [3], all CRs originate from our the Milky Way and its halo, and the contribution of other galaxies remains negligible. Here, we consider a different (strong) version of holistic models, where not only the same source, but also the same acceleration mechanism is operating over the whole spectrum of CRs, with the most simple source spectrum, namely a single power-law, in E^{-x}. This is a purely phenomenological study, since the actual CR source and acceleration mechanism are not specified. We simply assume that *some* mechanism produces a CR power-law spectrum in *some* sources located inside galaxies, and show that the resulting relative normalisation of Galactic and extragalactic components are as observed for the most natural value of the unique free parameter of the model, namely the logarithmic slope of the power-law, x.

2. Relative normalization of Galactic and extragalactic CR components

Let us assume that CRs are produced in our Galaxy with an average injection rate, in s^{-1} GeV^{-1},

$$q(E) = q_0 \left(\frac{E}{E_0}\right)^{-x}, \tag{1}$$

where q_0 is a normalisation factor, related to the global source power. In practice, it does not matter where and when the CRs are injected in the Galaxy, as long as the granularity of sources in space and time is small compared to the diffusion radius and confinement time of the cosmic-rays in the Galaxy. This amounts to assuming that the observed CRs are not significantly different from what would be observed at another time and somewhere else in the Galaxy, as usually assumed in CR source models. We choose $E_0 = 1$ GeV as the reference value for (low-energy) Galactic cosmic-rays (GCRs), because this is where the CR phenomenology (including propagation effects) is best known and constrained by composition measurements.

The CRs injected in the Galaxy are scattered by magnetic field inhomogeneities and remain confined for a time $\tau_{\rm conf}(E)$ that depends on their energy. At very high energy, say at $E \gtrsim 5\,10^{18}$ eV, the CR gyroradius is larger than the size of the confining region, and the CRs injected inside the Galaxy leak out freely and diffuse in the whole universe. Therefore, most of the high-energy CRs that are observed on Earth have an extragalactic origin. We choose $E_1 = 10^{10}$ GeV as the reference value for (high-energy) extragalactic cosmic-rays (EGCRs), because it is high enough for the corresponding CRs to have a diffusion radius (over the age of the CR sources) larger than the distance between typical galaxies, so that their density should be roughly uniform in the universe, and it is low enough for propagation effects due to CR interactions with the ambient radiation field to be negligible. This enables a straightforward calculation of the corresponding CR density.

At low-energy (and in a steady state), the local density of the GCRs is simply given by the total number of CRs injected during $\tau_{\rm conf}$ divided by the confinement volume, $V_{\rm conf}$:

$$n_{\rm G}(E) = q_0 \left(\frac{E}{E_0}\right)^{-x} \times \frac{\tau_{\rm conf}(E)}{V_{\rm conf}(E)} \tag{2}$$

At high-energy, many (extragalactic) sources contribute to the local density of EGCRs. Assuming that they accumulated uniformly throughout the universe since the onset of the high-energy activity of galaxies, the density of EGCRs is obtained as the number of CRs ever injected by a galaxy divided by its effective volume, $V_{\rm eff}$, i.e. the proper volume it occupies in the universe, with no overlap with other galaxies. If all galaxies are similar, this is simply $V_{\rm eff} = 1/n_{\rm gal}$, where n_{gal} is the density of galaxies in *today*'s universe. In practice, galaxies are of different types and one may expect that they inject CRs proportionally to their luminosity, so that their effective volume should also be scaled accordingly. Here, we take the Milky Way as a reference and thus use the density of Milky-Way-like galaxies in the universe: $n_{\rm gal} \simeq 3\,10^{-3}\,{\rm Mpc}^{-3}$ [4]. It should also be noted that cosmic-rays injected at redshift z with an energy $E_{\rm in}$ are now observed at energy $E = E_{\rm in}/(1+z)$. We thus obtain, integrating backward in time over the age of the universe:

$$n_{\rm EG}(E) = \int_0^T q(E_{\rm in}, t)\frac{{\rm d}E_{\rm in}}{{\rm d}E}{\rm d}t \times n_{\rm gal} = \int_0^\infty q(E_{\rm in}, z)\frac{{\rm d}E_{\rm in}}{{\rm d}E}\frac{{\rm d}t}{{\rm d}z}{\rm d}z \times n_{\rm gal}, \tag{3}$$

where we allowed for a time (redshift) dependence of the CR injection rate. Assuming that it is proportional to the star formation rate, we follow [5] and take $q(E,z) = q(E,0)f(z)$, where $f(z) \simeq (1+z)^4$ for $0 \le z \le 1.3$ and $f(z) = f(1.3)$ for $1.3 < z \le 5$ (see e.g. [6] and refs. therein). Replacing $q(E,0)$ from Eq. (1) and using standard cosmology with ${\rm d}z/{\rm d}t = H_0(1+z)[\Omega_{\rm M}(1+z)^3 + \Omega_\Lambda]^{1/2}$, one obtains:

$$n_{\rm EG}(E) = \frac{q_0 n_{\rm gal}}{H_0}\left(\frac{E}{E_0}\right)^{-x} \times I_{\rm cosmo}\,, \tag{4}$$

where the dimensionless integral taking into account the cosmological evolution can be approximated by

$$I_{\rm cosmo} = \int_0^{z_{\rm max}} f(z) \frac{(1+z)^{-x}}{\sqrt{\Omega_{\rm M}(1+z)^3 + \Omega_\Lambda}} {\rm d}z \simeq 25\, e^{-0.8x}, \quad (5)$$

with less than 3% error in the range of logarithmic slopes of interest (we have used $\Omega_{\rm M} = 0.27$ and $\Omega_\Lambda = 0.73$).

We can now derive the value of x for which a CR holistic model as considered here is possible. We simply need to identify the predicted value of $n_{\rm G}(E_0)/n_{\rm EG}(E_1)$, from Eqs. (2) and (4), with the measured value. We obtain:

$$x = \ln\left[25\, n_{\rm gal} \frac{V_{\rm conf}(E_0)}{H_0 \tau_{\rm conf}(E_0)} \frac{n_{\rm G}(E_0)}{n_{\rm EG}(E_1)}\right] / \ln\left[\frac{E_1}{E_0} \times e^{0.8}\right]. \quad (6)$$

As can be seen, the logarithmic slope of the injection spectrum is given here as a function of parameters that can be measured or derived directly from the astrophysical data. In addition to the numerical values already mentioned, we use $H_0 \simeq 65\,{\rm km\,Mpc^{-1}s^{-1}}$, a confinement time at 1 GeV equal to $\tau_{\rm conf}(E_0) \simeq 24$ Myr [10] and a confinement volume estimated from the recent propagation models that favour halo heights of the order of 5 kpc (above and below the Galactic plane)[11]: $V_{\rm conf} \simeq \pi \times (15\,{\rm kpc})^2 \times 10\,{\rm kpc} \simeq 7\,10^{-6}\,{\rm Mpc}^3$. As for the measured CR fluxes, at 1 GeV we take the CR differential flux deconvoluted from solar modulation[7]: $\Phi_{\rm CR}(1\,{\rm GeV}) \simeq 0.5\,{\rm cm^{-2}sr^{-1}s^{-1}GeV^{-1}}$, and at 10^{10} GeV, an average of AGASA and HiRes values[8, 9]: $\Phi_{\rm CR}(10^{10}\,{\rm GeV}) \simeq 2\,10^{-28}\,{\rm cm^{-2}sr^{-1}s^{-1}GeV^{-1}}$. Therefore, $n_{\rm G}(E_0)/n_{\rm EG}(E_1) \simeq 2.5\,10^{27}$. Reporting all the quantities in Eq. (6), we find:

$$x \simeq 2.31 \pm 0.07, \quad (7)$$

where the error bars account for an uncertainty as large as a factor of 5 on the quantity $I_{\rm cosmo} \times (n_{\rm gal} V_{\rm conf}/\tau_{\rm conf})$ (all other parameters are known with a much better precision).

3. Discussion

The result given in Eq. (7) reads as follows: holistic CR source models (where CRs of all energies are produced by the same sources with a single power-law spectrum) are indeed possible, and the corresponding value of the logarithmic slope is determined unequivocally from measured parameters to be $x \simeq 2.3$. This is remarkable in several respects. Not only could a working value of x be found, but the solution $x \simeq 2.3$ is particularly interesting from the phenomenological and theoretical points of view. This slope is in keeping with common expectations, being similar to that obtained from relativistic shock acceleration, or for internal shock models of gamma-ray bursts, for instance. It is also right in the middle of the allowed range for low-energy CRs, as derived from detailed studies of the secondary-to-primary composition ratios (e.g. [11, 12]).

The obtained value of x is also particularly interesting in relation with EGCRs. While the best fit of the highest-energy data is usually obtained with a source spectrum in $E^{-2.6}$[13], this result only holds for pure proton sources. Most (if not all) astrophysical sources of CRs would however accelerate heavier nuclei just as well, since electromagnetic processes only depend on the charged particle rigidity. Quite remarkably, it is found that when assuming a similar composition for EGCRs and GCRs (as would of course naturally be the case in a holistic model), the high-energy data are best reproduced by a power-law source spectrum in $E^{-2.3}$ [14, 15]. Therefore, the source spectrum that makes holistic models viable is precisely the one that is consistently favoured at low energy, from GCR phenomenology, and independently at high energy, from EGCR phenomenology.

Even though it is simple, the above analysis is quite robust. The most uncertain parameters are the CR confinement volume at 1 GeV and the density of Milky-Way-equivalent galaxies in today's universe. However, even large variations of these parameters cannot change the value of x substantially. This is due to the huge lever arm between low-energy GCRs and high-energy EGCRs. It should also be noted that the determination of x does not depend on any assumption concerning the energy dependence of the CR confinement time. We simply used the value derived from the CR data at $E_0 = 1$ GeV. Interestingly, however, it then leads to a determination of the confinement time that would allow one to reproduce the observed GCR spectrum, in $E^{-2.71}$: $\tau_{\rm conf}(E) \propto E^{\delta}$, with $0.33 \lesssim \delta \lesssim 0.47$, which is also the range expected from CR diffusion theory.

In conclusion, we found that a holistic CR source model with a single power-law spectrum in E^{-x} and $x \simeq 2.3 \pm 0.07$ could account for the cosmic rays at all energies, in keeping with known results concerning the phenomenology of both low-energy and high-energy CRs, and in agreement with the main theoretical results concerning CR acceleration and transport. However, it should be clear that we did not propose here a well-defined physical or astrophysical model. We simply made a general phenomenological remark that may motivate or encourage further studies of the origin of CRs considered globally, as a general phenomenon possibly involving a single process at work over their whole energy range.

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