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The energy at which the intensities of the extragalactic and galactic cosmic rays equalize

Antonio Codino[a]

(a) Dipartimento di Fisica dell'Universita' degli Studi di Perugia e INFN, Via A. Pascoli, 06123 Perugia, Italy

Presenter: Antonio Codino (antonio.codino@pg.infn.it), ita-codino-A-abs1-he13-oral

A variety of observational data suggest that cosmic rays below the knee energy are accelerated in the Galaxy while those beyond the ankle outside. The extragalactic and galactic components of cosmic rays are intermixed in the solar cavity, by quite different amounts, depending on the energy. The purpose of this study is to determine that particular energy where the two components become equal. Using undisputed, reliable, observational facts regarding the galactic magnetic field, the position of the solar cavity in the Galaxy, the size of the disk and halo, the interstellar matter density, and the inelastic nuclear cross sections, properly blended in simple algorithms, the equalization energy of the two components is calculated. The equalization of the two components for Helium takes place around the energy of $5.5 \times 10^{16}\ eV$. When the intervals of the parameters mentioned above are allowed to vary within the experimental limits, the above value shifts to a minimum of $2 \times 10^{16}\ eV$ and to a maximum of $7 \times 10^{16}\ eV$. The equalization energy of heavier cosmic rays is close to these figures.

1. Introduction

The intensity of cosmic rays arriving at the solar cavity, I, may be subdivided in two components depending on the position of their sources. Denoting the galactic and the extragalactic sources by I_g and I_e, respectively, one can write:

$$I = I_g + I_e$$

Galactic cosmic rays dominate the energy spectrum below the knee energy, while extragalactic cosmic rays dominate the spectrum at energies higher than the ankle energy. Traditionally the knee energy is at 3×10^{15} eV and the ankle energy at about $5 \times 10^{18}\ eV$. In order to determine the energy of cosmic rays where the extragalactic component becomes equal to the galactic component, let us identify two comfortable energy intervals in the differential energy spectrum of the cosmic rays , where the dominance of one component is well established. The extragalactic component is believed to be negligible at energies below the knee. The dominance of the galactic component at low energy is based on γ rays intensities measured by many experiments in the energy interval 0.1 - 10 GeV [1,2]. From these is derived a spatial gradient along the galactocentric radius r, which indicates that cosmic-ray intensity is higher in the core of the Galaxy and lower in its periphery though this gradient differs significantly from that of supernovae [3]. These findings strongly suggest that the sources of the cosmic rays are in the Galaxy and not outside. Moreover, the detection of the electron component in many spiral galaxies by radiotelescopes also suggests the origin of low energy cosmic rays in the Galaxy [4] along with the measurements of the residence times of cosmic rays by radioactive clocks.

The extragalactic component should dominate at those energies where the field strength of the Galaxy is not sufficient to retain cosmic rays for long time. This certainly takes place at energies beyond $10^{19}\ eV$ but detailed calculations, like those reported here, demonstrate that the extragalactic component is robust and dominant even at lower energies, down to $10^{17}\ eV$. From these observational facts it follows that there should be an energy where the two components I_g and I_e join together and exchange the role, from dominant to marginal, and $viceversa$.

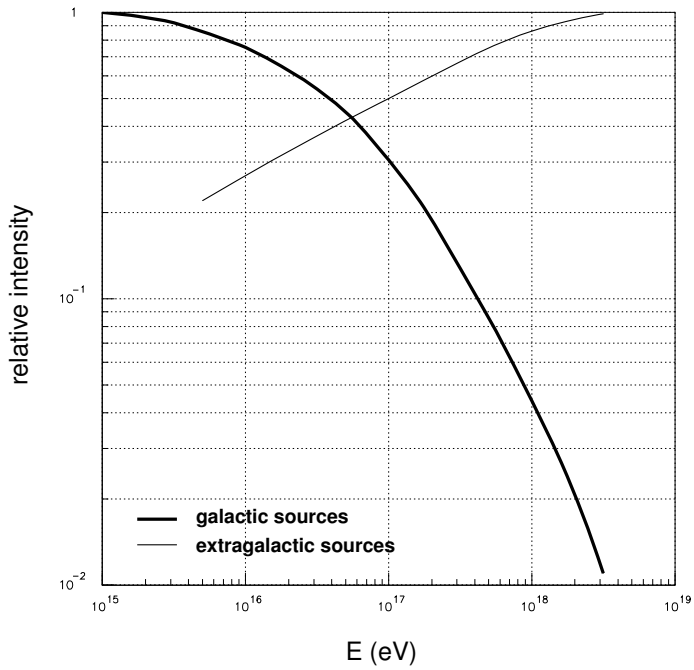

Figure 1. Computed intensity of galactic (thick line) and extragalactic (thin line) cosmic rays observable in the local galactic zone versus energy. The galactic component is normalized at 10^{15} eV and the extragalactic one at 10^{19} eV as explained in the text.

2. Some relevant parameters of the calculation

There are four basic parameters used in the calculation. The size of the Milky Way, the matter density in the interstellar space, the galactic magnetic field, and the inelastic nuclear cross sections. All these parameters are based on numerous observational data, more than adequate for the accuracy of this calculation. Cylindrical coordinates r, z with the origin in the galactic center are used. The gaseous disk has a radius of 15 kpc, half thickness of 120 pc up to 9.5 kpc, then enlarges linearly with r to the value of 375 pc at 15 kpc. Interstellar matter consists only of hydrogen; its density in the galactic midplane reaches a maximum of 2.4 atoms per cm^3 at the radial distance of 4.6 kpc, decreasing to the value of 1.3 at 8.5 kpc and down to 0.11 at 15 kpc. There is an exponential decrease of the density along z. The configuration of the galactic magnetic field incorporated in the algorithms is described elsewhere [5,6]. Cosmic rays are studied using the method of the trajectories utilized in previous works (see for example [5,6,7], upgraded by new algorithms appropriate for ultrahigh energy cosmic rays, as reported in another paper of this conference [8].

3. Results of the calculation

In order to calculate n_g cosmic-ray trajectories are propagated in the galactic disk and those intercepting a recording instrument at Earth are counted. A small sphere, 50 pc in diameter is used to count the number of cosmic rays, n_g. Note that both n_g and n_e are proportional to I_g and I_e, respectively. Galactic sources are distributed in space as supernove remnants. In figure 1 is given n_g versus energy (thick line) . The fall of n_e above 10^{16} eV reflects the inefficiency of the magnetic field to retain cosmic rays as the energy increases. Figure 2 shows the grammage encountered by the galactic cosmic rays traversing the Galaxy for the disk and the halo, separately. Above the energy of 5×10^{17} eV manifests itself the inefficiency of the magnetic field to bend particles and above 3×10^{18} eV the grammage attains its asymptotic limit.

In principle the intensity of the extragalactic component at Earth, n_e, can be calculated by injecting cosmic rays from the halo frontier, reconstructing and counting cosmic-ray trajectories intercepting an appropriate instrument at Earth. This direct method has severe computational drawbacks and it is not used here. A more efficient method takes advantage of the reversilibility of the trajectories in a magnetic field as explained elsewhere [9]. In order to determine n_e all cosmic rays are injected from the Earth into the galactic volume and only those reaching the halo frontier counted by n_e. The halo frontier is an ellipsoid: $z = (a^2 - b^2 \times r^2)^{1/2}$ where $a = 100$ and $b = 11.11\ 10^{-2}$ kpc^2. The number n_e versus energy, for helium nuclei, is reported in figure 1 as a thin line.

4. Interpretation of the results and conclusions

In the following it is analyzed the logical chain to establish the equalization energy, E_e for Helium at Earth. Let us summarize the hypothesis : (α) there are two energy regions where the galactic and extragalactic component separately dominate. In another paper [10] it is postulated that a universal acceleration mechanism operates everywhere, inside galaxies and in the intergalactic space, at least within 30 Mpc from the Milky Way, shaping and setting the spectral index of cosmic rays at the approximate value of 3. This postulate is anchored to some basic observations regarding the differential energy spectrum, the arrival directions of cosmic rays beyond 4×10^{19} eV and others. Out of all possible modes, the extragalactic and galactic components might have joined together between 10^{14} and 10^{18} eV, as a matter of fact, the differential energy spectrum measured by many experiments unmistakably indicate a smooth, regular transition. Profound dips, spikes or undulations in the energy spectrum are not observed. Let us translate all that in a form (hypothesis (β)) useful here : the components I_g and I_e join together approximately with the same spectral index. In the present context, without the hypothesis (β), the determination of E_e is not possible because n_e and n_g versus energy are unmeasured and unknown at Earth and they might differ by orders of magnitudes in a given galactic location for a given energy. Adopting the hypothesis (β), the curves n_g and n_e versus energy in figure 1 are normalized to their maximum values in the those regions where n_e and n_g separately dominate. The equalization energy is obtained by overlapping the curves in figure 1. From the results in figure 1 the equalization energy for Helium results 5.5×10^{16} eV.

The results shown in figure 1 and their interpretation silently assume that the energy spectrum at the galactic sources, in the full energy range, e. g. from 10^{10} to 10^{20} eV, has a constant spectral index; this index is believed to be lower than 3 below 3×10^{15} eV because of the propagation effects in the Galaxy. According to many authors the acceleration mechanisms in the Galaxy become highly inefficient as the energy increases, in the interval 10^{14} to 10^{17} eV. Hence, n_g versus energy in figure 1 delimits the maximum intensity of galactic cosmic rays at Earth. In this circumstance the equalization energy for Helium have to shifted to a value lower than 5.5×10^{17} eV and accordingly E_e given above is overestimated.

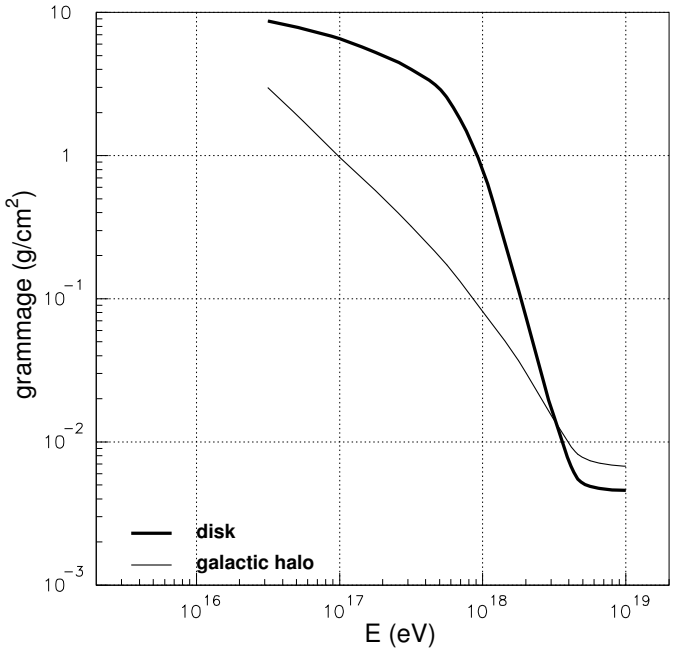

Figure 2. Gas column (grammage) versus energy encountered by galactic cosmic rays with sources distributed as supernovae remnants in the galactic disk (thick line) and in the halo (thin line).

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