29th International Cosmic Ray Conference Pune (2005) **3**, 253–256

Ultrahigh energy cosmic rays beyond the ankle are accelerated in the space between galaxies

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The spectral index of the differential energy spectrum of all cosmic rays is 3 in the largest energy interval best measured, from 10^{16} to 10^{19} eV, and close to 3 at lower energies. It is regarded as an unlikely occurrence that a variety of different acceleration mechanisms, active with variable efficiency in different energy intervals, operating in quite dissimilar cosmic regions, injecting ions from hydrogen to uranium, would finally cooperate to yield a unique spectral index. On the contrary it is suggested, using observational data and logical arguments, that this constant spectral index, spanning over 29 orders of magnitudes in cosmic-ray intensities, is compatible with a unique acceleration mechanism operating in the universe and not with numerous, heterogeneous ones. Measurements of the magnetic field strengths in spiral galaxies, like the Milky Way, comprised between 1 and 15 μG, indicate that particles with energy exceeding 10^{18} eV cannot be retained in the galactic volumes. From this evidence and other facts suggesting that the sites of acceleration of ultrahigh cosmic rays cannot be galactic, is inferred that cosmic rays suffer acceleration in the space between galaxies.

1. Introduction

In figure 1 is shown the differential energy spectrum measured by many experiments and recently by the HiRes and AGASA Collaborations [1] at the maximum energies. A remarkable aspect of this spectrum is the approximate equality of the spectral index in a huge energy interval which yields a rather uniform flux versus energy, in the appropriate variables. The uniformity of the energy spectrum is not only surprising but is also an important distinctive characteristic because the intrinsic nature of cosmic-ray acceleration would better call for many different unmatched spectral indexes, due to the very large energy interval involved. The uniformity of the spectrum is qualitatively utilized to discuss and derive the two tenets of this study: (I) high energy cosmic rays undergo acceleration in the space between galaxies; (II) only a universal mechanism accelerates high energy cosmic rays both in galaxies and in the intergalactic space. Before deriving the main results of the paper, let us highlight the surprising aspect of the spectrum.

Assuming that the acceleration mechanisms follow the Fermi scheme, the spectral index is given by: $\gamma = f$ T_a T_c^{-1} where f is the fractional energy gain per encounter, T_c is the time required for the acceleration of cosmic rays and T_c is the residence time spent by cosmic rays in the acceleration region. In principle, the spectral index γ may assume a wide range of values in view of the large variety in the dimensions of cosmic regions and magnetic field strengths occurring in nature. For instance, if a very specific class of galaxies (for example Seyfert, AGN, powerful radiogalaxies etc.) would accelerate cosmic rays with a spectral index close to 3, it seems unlikely that the ensuing energy spectrum emanating from such specific galaxies would accord harmoniously, matching f, T_a and T_c, with that observed at Earth belonging to a normal spiral galaxy. A universal spectral index, one independent of the parameters T_c, T_a and f, is that adopted for studying ion acceleration in blast waves from supernovae but it is close to 2.1 and valid only in a limited energy interval. Many examples of known cosmic regions suggest that T_a, T_c should largely differ, as well as the fractional energy gain f. It makes it difficult to explain the same γ in the full range of the spectrum, without assuming a single acceleration mechanism everywhere.

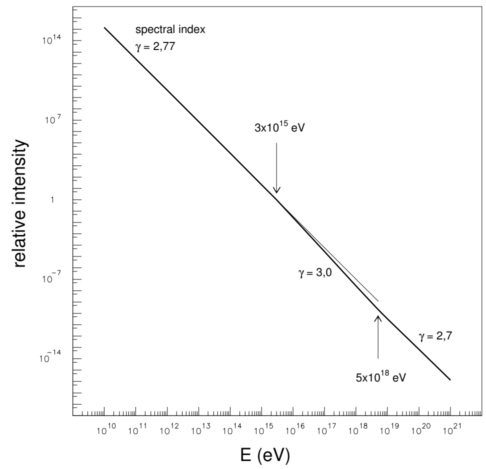

Figure 1. Differential energy spectrum of the cosmic radiation from 10^{10} $eV$to the maximum energy measured to date 3×10^{20} eV. Due to the effect of the solar modulation the spectrum tends to an arc below 10^{10} eV . The energy of about 5×10^{18} eV marks the ankle energy, firstly measured by the Haverah Park experiment.

2. Ultraenergetic cosmic rays are not galactic

Multiple arguments indicate that the sources accelerating cosmic rays beyond 10^{18} eV are not placed in the Galaxy. Two major arguments, quite independent, referred to as (a) and (b) are given below.

(a) The measured magnetic field strength in the Galaxy, ranging from 1 to 5 μG, cannot bend or invert efficiently the direction of motion of cosmic rays in the gaseous disk because of its small thickness, less than 200 pc. As a result, disk sources of ultrahigh energy cosmic rays, if any, would exhibit a large depletion in the differential energy spectrum observable at Earth. Using computer simulation of cosmic-ion trajectories, the computed depletion is a factor 25 at 10^{18} eV as shown in figure 2. This depletion does not exist in the experimental data, where, on the contrary, a smooth, uniform spectrum with $\gamma = 3$ is observed. From this result it follows that ultrahigh cosmic rays are not accelerated in the Galaxy. In this derivation it is implicitly assumed that acceleration mechanisms in the Galaxy operate with the same efficiency above 10^{15} eV as they do at lower energies, which is certainly unlikely at the theoretical level. Note also that the result shown in figure 2 is anchored only on the magnetic field strength and the disk size; it is rather insensitive to the collective motions of the interstellar plasmas or, equivalently, to the spectrum of magnetic inhomogeneities adopted for shaping cosmic-ion trajectories such as kolmogorov, kraichnan or others.

(b) Any source distribution placed in the disk would yield a flux enhancement clustering in the galactic midplane with respect to other directions in the sky. Using a plane enhancement parameter f_E [2] for a quantitative analysis, no evidence has been reported to date for an unmistakable correlation between the arrival direction of ultrahigh cosmic rays and the galactic plane [3].

From (a) and (b) follows that the sources of ultrahigh energy cosmic rays are not galactic. Furthermore, specific mechanisms conceived for ion acceleration in the Galaxy, like those envisaged in circumstellar space of supernovae or other stars, have an intrinsic limitation in providing ion energies exceeding $10^{15}\ eV$ [4, 5]. This theoretical limitation reinforces the case for the extragalactic origin the ultrahigh energy cosmic rays.

3. Peculiar galaxies within 30 Mpc do not emanate ultrahigh cosmic rays

If cosmic rays with energy above $2 \times 10^{18}\ eV$ are not accelerated in the galactic volume, they have to be accelerated outside the galactic boundaries. Let us proceed further showing why $peculiar\ galaxies$ cannot accelerate cosmic rays above $4 \times 10^{19}\ eV$. A partition of all space presently conceivable, $a\ priori$, for cosmic ray acceleration may be subdivided in two separate regions: galaxies and the rest, i.e. all space regions outside galaxies, the intergalactic space. The galactic volume being the disk or the halo for spirals, and similarly, for elliptical and spherical galaxies.

The attenuation length of cosmic protons above $10^{19}\ eV$ sets an important bound on the maximum extension from the Earth where ultrahigh cosmic ions are accelerated. This size amounts to about 30 Mpc. Cosmic protons exceeding $10^{19}\ eV$ interacting with the microwave background radiation should generate a depletion in the energy spectrum around $4 \times 10^{19}\ eV$. Such a depletion, called GZK cut-off, amounts to about 40 per cent at the energy of $8 \times 10^{19}\ eV$ and less than 5 per cent at $3 \times 10^{20}\ eV$. The expected cut-off has never been observed [6, 7, 8]. This important finding allows to rule out any type of peculiar galaxy in the cosmic vicinity of 30 Mpc as a cosmic-ray propeller. In fact, since the mean deviation angle at the highest energies is comfortably small (a few degrees) and the positions of peculiar galaxies are known within 30 Kpc, by extrapolating backward the arrival directions of ultrahigh energy cosmic rays, it is possible to identify the source region. The distribution of arrival directions of cosmic rays with energies exceeding $10^{19}\ eV$ is isotropic [1] ; peculiar galaxies are ruled out as cosmic ion accelerators as reported in a detailed study [9] and AGN too [9]. Moreover, since the largest concentration of galaxies close to the Earth is in the Virgo cluster (more than 2500 galaxies at 20 Mpc), it is interesting to examine cosmic rays arriving from this direction. There is no observational evidence for a preference in the arrival directions of ultrahigh cosmic rays pointing to Virgo [10].

4. Conclusions and remarks

From the arguments given above ultrahigh energy cosmic rays are accelerated neither in the Milky Way nor in peculiar galaxies in our vicinity, within 30 kpc. Therefore they are accelerated in the intergalactic space. To proceed further two observational facts have to be considered : (I) The sources of low energy cosmic rays are in the Galaxy; (II) the uniformity of the energy spectrum between 10^{10} and $10^{20}\ eV$. The relevance of the uniformity has been concisely qualified in the Introduction.

The spectral index after acceleration can be modified by several factors : confinement times in given regions which are regulated by the magnetic fields, nuclear cross sections varying with energy, radiative processes, threshold nuclear processes and reaccelerations by any mechanisms. At ultrahigh energy some of these processes become inefficient to modify the energy spectra emanated by the extragalactic sources.

Detailed calculations indicate that the gas column (grammage) encountered by extragalactic cosmic rays above $10^{18}\ eV$ reaching the Earth, penetrating the halo and the disk, is quite modest, on average less than 10^{-3} g/cm^2. Thus the distortion of the energy spectrum due to the galactic magnetic field and to nuclear cross sections dependent on energy, is negligible. The magnetic field indirectly affects the grammage by causing cosmic rays to pass many times through the same region. Hence, cosmic rays with energies above $10^{18}\ eV$ reaching the Earth have the same spectral index existing in the extragalactic sources.

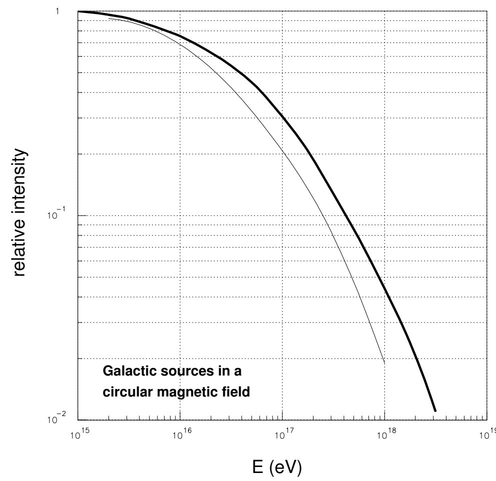

Figure 2. Number of cosmic rays registered by a small sphere positioned in local galactic zone versus energy normalized at 10^{15} eV. The thick line refers to a magnetic field structure with a field strength of about 3 μG while in the thin line the strength is reduced by an arbitrary factor of 3 to single out the effect of the galactic magnetic field on the cosmic ray intensity. Galactic sources are distributed as supernovae remnants.

If cosmic-ray sources below $10^{14}\ eV$ are positioned in the disk of the Milky Way and those of ultrahigh energy are extragalactic, one obvious conclusion is that a single, unique, mechanism operates both inside and outside galaxies in such a way to give the same spectral index. This conclusion follows , simply and straightforwardly, from the observed uniformity of the spectral index and from the realization that the extragalactic energy spectrum at these extreme energies observed at Earth cannot differ from that existing in the cosmic vicinity, within 30 Mpc. In a forthcoming paper we describe the physical mechanism that accelerates cosmic rays.

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