Physics – Uspekhi **39** (2) 155 – 168 (1996)

REVIEWS OF TOPICAL PROBLEMS PACS number: 98.70.Sa

Cosmic ray astrophysics (history and general review)†

V L Ginzburg

Contents

Abstract. The history of the discovery and investigation of cosmic rays prior to the advent of the cosmic ray astrophysics is presented. Some data about cosmic rays near the Earth and in the Universe are given. The main part of cosmic rays observed near the Earth is generated in our Galaxy by supernova explosions. The most important problem yet to be solved in cosmic ray astrophysics is the origin of cosmic rays of superhigh energy.

1. Short history of the discovery of cosmic rays

The history of the discovery of cosmic rays may be thought to be rooted in 1900 when Elster and Geitel [1] and Wilson [2] independently came to the conclusion that pure air in a closed vessel possessed some electrical conductivity. Meanwhile, no visible sources of air ionisation were observed. It was already known at that time that X-rays and radioactivity were factors contributing to the enhanced electric conductivity of gases. Therefore, the observed effect of 'dark current', which was due to residual ionisation of the air, was associated with radioactive contamination both in the air and in the environment (vessel walls, the Earth). True, as far back as 1901, Wilson hypothesized [3] that residual ionisation was due to certain highly penetrating radiation coming from outside the Earth's atmosphere. But this was mere speculation which was soon rejected by Wilson himself [4, 5]. However, the hypothesis of penetrating radiation of extraterrestrial origin was not completely forgotten even though it was viewed as improbable [6].

Thus, the observed ionisation was associated with radioactivity, specifically with gamma-ray emission of radioactive elements. For a long time, the results remained contradictory and unclear. For example, although screening the experimental device (electroscope) with rather a thick layer of lead slowed down ionisation, it remained at six ion pairs in 1 cm^3 per second [7]. This seemed to suggest that ionisation came from the walls of the apparatus. However, some uncertainty still remained, and the equipment was improved to allow recording devices to be placed higher and higher to clarify the role of radiation coming from the Earth, first to the Eiffel tower then to high-altitude balloons. It was at that time that Victor Hess (1883–1964) managed to clear up the problem. A total of ten flights were taken by Hess (two in 1911, seven in 1912, and one in 1913). He made observations in an open cabin (gondola) with two other men on board a balloon; they sometimes had to breathe oxygen. During his most successful flight on August 7, 1912, he reached the height of 5,350 m above sea level and obtained unequivocal evidence of a rather strong ionisation speed-up beginning from the height of about 2,000 m [8]. Specifically, in one of the two instruments used by Hess in which a constant pressure was maintained (a methodologically important point!), 15 – 16 ions/cm^3 were formed on the average at sea level and up to the height of 2,000 m, while the mean ionisation rate at 4,000 – 5,200 m was as high as 34 ions/cm^3; the other apparatus showed similar values.

The measurements Hess took during several flights suggested the following conclusion [8]: "The results of the present observations seem to be most readily explained on the assumption that radiation of very high penetrating power enters the atmosphere from above; even in its lower layers, this radiation produces a part of the ionisation observed in closed vessels... Since there was no decrease in radiation either

† Report presented at the Conference on Cosmic Rays, Particle and Astroparticle Physics (Florence, September 10 – 13, 1995). The text of the report is virtually unaltered but supplemented with the Appendix specially written for 'Physics–Uspekhi'.

V L Ginzburg P N Lebedev Physical Institute, Russian Academy of Sciences, Leninsky prospect 53, Moscow 117924 GSP, Russia
Tel. (095) 135-85-70
Fax. (095) 938-22-51

Received 27 September 1995
Uspekhi Fizicheskikh Nauk **166** (2) 169–183 (1996)
Translated by Yu V Morozov, edited by A Radzig

at night or during the solar eclipse, the Sun can hardly be considered as a source of this hypothetical radiation, at least so long as one thinks only of direct gamma-emission with rectilinear propagation''.

August 7, 1912, the date of Hess' most successful flight, is generally believed to be the date of the discovery of cosmic rays.

Today, the results obtained by Hess seem quite convincing. But it was not always so. His measurements met with objections, first of all on the part of a German physicist Kolhorster, who believed that the change in the ionisation rate with increasing height was due to temperature variations. Kolhorster constructed a more sophisticated instrument and made five balloon flights in 1913 and 1914, eventually reaching the height of 9,300 m [9]. Despite his intention to 'shut down' the discovery of Hess, Kolhorster fully confirmed it. At a height of 9,000 m, the ionisation rate amounted to 80 ions/cm^3 and was approximately 40 times that at sea level. Kolhorster called the source of ionisation the 'high-altitude radiation' (Hohenstrahlung); it was also called 'Hess radiation' (Hess'sche Strahlung). Hess himself preferred the term 'ultragamma-radiation' (Ultragammastrahlung). The present name 'cosmic rays' was given by Millikan in 1925 [10]. By the way, Millikan and his colleagues had long doubted that increased ionisation was actually induced by some radiation coming from outer space. Ionisation was assumed to originate from radioactive elements accumulated in the upper atmosphere. This hypothesis was decisively disproved only in 1925 [10] (see Ref. [4] for more details).

Thus, doubts concerning the existence of cosmic rays were ultimately resolved only by 1925 – 1926. In the meantime, from the very beginning it had been assumed that these cosmic rays were gamma-rays albeit harder than the known gamma-rays of radioactive origin [8]. Such an assumption appeared quite relevant because it is precisely gamma-rays, of all types of radioactive radiation, that display the highest penetrating ability. The high penetrating power of ultra-relativistic charged particles was then unknown. This problem will be discussed below. Here, it is worthwhile to note that the term 'cosmic rays' currently refers solely to fast charged particles of cosmic origin. Cosmic gamma-ray emission also exists, but it is called cosmic gamma-rays and is the subject of gamma-astronomy.

It is also noteworthy that Hess was awarded the Nobel prize for physics only in 1936, 'for his discovery of cosmic radiation'. Actually, Hess received half of the prize because the second half was given to Anderson for his discovery of the positron [11]. According to the Nobel Prize status, the award had to be given 'for the latest discoveries ..., and only for those earlier ones whose significance had not until recently been clarified'. The fact that Hess became a Nobel Prize winner 24 years after he had discovered cosmic rays leaves little room for doubt that the discovery had long been disputed before its significance was duly appreciated. At present, by the way, the above-mentioned limitation is the exception rather than the rule.

As it is, Clay was the first to report in 1927 the presence of charged particles in primary cosmic rays near the Earth [12]. Specifically, he observed the geomagnetic effect at sea level, i.e. the dependence of cosmic ray intensity (ionisation rate) on geomagnetic latitude. At the geomagnetic equator, the intensity of cosmic rays is 10 – 15% lower than at high latitudes. Obviously, gamma-rays cannot be responsible for the latitude effect. Clay had not however provided any explanation for the observed effect. The correct interpretation was given by Bothe and Kolhorster only in 1929 in a paper devoted to the detection of highly penetrating charged particles as indispensable components of cosmic rays with coincidence-recording Geiger–Muller counters [13]. Incidentally, such particles with indisputably high energy had earlier been observed by Skobeltzyn [14].

Thus, sea-level studies of fast charge particles and geomagnetic effect suggested that at least a part of primary cosmic rays entering the atmosphere consisted of charged particles [13]. A further important contribution was the experiments carried out by Rossi [15], who modified the coincidence technique and found that cosmic rays contained particles with a very high penetrating power; also, the ability of charged particles in cosmic rays to generate secondary particles was shown [15, 4, 5].

A large number of papers have been devoted to the study of geomagnetic effects, in the first place the latitude effect, and many painstaking efforts were made to solve this problem [4, 5]. The point is that the results of measurements seemed conflicting in more than one respect. At present, we understand that this was largely due to the fact that at high latitudes (about 50° or higher), geomagnetic latitude effect cannot be observed at sea level. The explanation is very simple: particles with energy below 4×10^9 eV (and their products) are absorbed in the atmosphere, and the expected increase of their flow at the atmosphere boundary 'does not reach' as low as sea level. The nature of the latitude effect was finally clarified in 1932 by Compton, who organised a number of expeditions for the purpose of making measurements at 69 points throughout the globe using the same technique [16]. As a result, the latitude effect was unambiguously confirmed to occur. But this study gave no evidence that all primary cosmic radiation was of corpuscular nature — a part of cosmic rays might just as well consist of gamma-photons. This was precisely how Compton saw it [16] when he arrived at the conclusion (based on the comparison between the theory of geomagnetic effects and direct observations) that the energy of charged components in primary cosmic rays was in the range from 5×10^9 to 1.3×10^{10} eV.

Besides the latitude effect, there is a separation of positively and negatively charged particles entering the atmosphere caused by the Earth's magnetic field. As a result, the so-called east-west asymmetry must occur if the numbers of positively and negatively charged cosmic ray particles are not identical, that is particle fluxes from the east and from the west must be different [17] (see also [5]). At first, Rossi failed to see this effect, but later on (in 1933) Johnson [18], Alvarez and Compton [19], and again Rossi [20] observed in their experiments the east-west asymmetry prevailed by positively charged particles. Had this conclusion been drawn a year or two earlier, primary cosmic rays would have been assumed to consist largely of protons and heavier nuclei. But in 1932, positrons were discovered [11] and at first were thought to be particles that constitute cosmic rays. However, a more detailed study of geomagnetic effects at sea level and on the Earth in general led Johnson to conclude in 1938 [21] that the dominant particles in primary cosmic rays were protons. This assumption was validated in 1940 by Schein and his group [22]. They carried out balloon measurements up to the height of 20,000 m where primary particles were mostly recorded. By that time, showers in cosmic rays had already been discovered and patterns of absorption of proton and electron-positron components by the matter had generally

been established. Specifically, it was shown that the electron-positron component produced showers, whereas protons of the same energy did not. That is why, using a device with several lead-separated counters [22], it was found that primary particles were protons and produced virtually no showers.

Forestalling events, it should be noted that a subsequent investigation of the primary component by recording showers in Wilson's cloud chamber at high latitudes demonstrated [23] that shower-producing particles (electrons, positrons, and photons) were less than 1% of the total number of protons (meaning electrons with energy higher than 10^9 eV). This result was obtained between 1950 and 1952. It was only in 1961 that Earl first discovered electrons with energy exceeding 5×10^8 eV contained in primary cosmic rays [24].

It was before the role of the electron component was elucidated [23] that a new technique had been applied (photographic emulsions were taken to the stratosphere). Using this method, it was found in 1948 that primary cosmic rays contain nuclei of various elements including iron [25, 26]. Some information about the nuclear component is presented below. For now, suffice it to say that, by and large, protons make up about 90% of all primary cosmic ray components while helium nuclei (α-particles, i.e. $^4He^{2+}$) amount to nearly 10%, and all other nuclei comprise only around 1% of the total flux.

2. On cosmic ray astrophysics

Thus, only about 40 years after Hess' flights, it was established that the Earth receives cosmic rays from outer space, that is ionising "radiation" consisting of protons and high-energy nuclei. But cosmic ray sources are not readily visible. Moreover, cosmic rays near the Earth are isotropic, that is they come from all sides with the same intensity (the action of the magnetic field of the Earth being assumed to have no effect whatever).† This explains why cosmic ray astrophysics has at that time been out of the question even though these rays may be regarded as an astronomical object. The situation was similar to the one that would exist if there were only integrated optical radiation from the Sun, all the stars and nebulae observed, without the possibility of seeing its sources (such a situation can be imagined to occur on a hypothetical planet with a very thick light-scattering atmosphere). Cosmic ray astrophysics was born in the early 1950s when it became possible to observe cosmic rays far from the Earth. Certainly, we mean the development of radioastronomical methods, specifically observation of cosmic radiation of synchrotron nature. We have no way here to dwell on the history of this line of research and must confine ourselves in this context to references to pioneering papers [27 – 30], books of collected articles [5, 31], and monographs [32, 33].

The essence of the matter is well known and will be briefly discussed below. For now, it will be sufficient to mention that relativistic electrons which form the electron component of cosmic rays (the intensity of this component near the Earth is approximately one percent of the intensity of the proton-nuclear component) emit radiowaves (the synchrotron mechanism) as they move in cosmic magnetic fields. Because radiowaves propagate rectilinearly, the reception of cosmic radioemission provides a tool to obtain information about the electron component of cosmic rays at a distance from the Earth, in our Galaxy, other galaxies, and quasars. Proceeding from certain assumptions, it is also possible to obtain data on all cosmic rays in the Universe. In other words, the radio-astronomic method helps to 'see' cosmic rays in interstellar space, various nebulae (in particular, in supernova remnants), and other galaxies. Also, synchrotron radiation may sometimes be observed in the optical and X-ray ranges.

Beginning in 1972, gamma-radiation (with energy exceeding 30 – 50 MeV) due to the decay of π^0-mesons generated in outer space on collisions between the proton-nuclear component of cosmic rays and atomic nuclei of interstellar space used to be detected during satellite flights. This provided direct information about the bulk of cosmic rays travelling far from the Earth. Generally speaking, the appearance of gamma-astronomy significantly broadened the possibility to study cosmic rays in the Universe, for cosmic gamma-photons with a sufficiently high energy are generated only by cosmic rays especially as a result of the aforementioned π^0-meson production. Cosmic rays must also generate neutrinos. Such cosmic neutrinos (as distinguished from the neutrinos produced by cosmic rays in the atmosphere and deep in the Earth) have not yet been recorded, but this appears to be a matter of the near future [33, 34].

To summarise, cosmic ray astrophysics is now based on investigations into primary cosmic rays near the Earth, on radio and gamma-astronomy. Of course, all other astronomical information is extensively used.

The state of cosmic ray astrophysics before 1990 is reflected in the monograph [33] and the literature cited therein. Certainly, more comprehensive and updated information can be found in the proceedings of the biennial International Cosmic Ray Conferences (ICRC). The 23d ICRC was held in Calgary (Canada) in July 1993 and the 24th ICRC took place in Rome in August–September 1995 (see the Appendix at the end of this report).

3. Cosmic rays and high-energy physics

It is well known that interest in cosmic rays had been great even before cosmic ray astrophysics appeared around 1950-1953. This was due to the fact that prior to the construction of modern accelerators, high-energy particles could have been observed only in cosmic rays. This explains why cosmic rays remained for a long time (up to the mid-1950s) a most important subject of high-energy physics. Showers in cosmic rays were reported [14, 15, 35, 36, 4, 5], the positron was discovered in 1932 [11] followed by $\mu^{\pm}$-leptons (muons) in 1937 [37, 38, 4, 5] and $\pi^{\pm}$-mesons in 1947 [39, 4, 5]. Later (between 1947 and 1953), K^+- and K^0-mesons, Λ^0-, Ξ^-- and Σ^+-hyperons were first reported to occur in cosmic rays [4].

From the mid-1950s, the interest in cosmic rays shown by high-energy physics fell sharply for two reasons. First, high-performance accelerators became available for experimental studies. Second (even if of lesser importance), cosmic ray astrophysics arose, which somehow diverted the attention of scientists from cosmic ray physics. However, investigations of cosmic rays in the so-called nuclear aspect continued and are still underway [41].

In connection with this, we think it is appropriate to make only one remark.

Cosmic rays cannot compete with an accelerator as soon as the necessary energy is available with the latter device. The

† In fact, there is some anisotropy δ of not more than a fraction of a percent. However, it is due to either high-energy particles or soft cosmic rays of solar origin [4, 5].

highest proton energy currently reached on the accelerator amounts to 900 GeV (Fermi Laboratory). Due to the presence of head-on beams in an accelerator, 900 GeV is the proton energy E_c in the centre-of-mass system. In cosmic rays, the energy E_c of a proton (in the centre-of-mass system) colliding with a proton at rest is reached at the energy (M is the proton mass)

$$E = \frac{2E_c^2}{Mc^2} - Mc^2 \approx \frac{2E_c^2}{Mc^2} \approx 2 \times 10^6 \text{ GeV} = 2 \times 10^{15} \text{ eV}. \tag{1}$$

Thus, it is now generally possible to use cosmic rays for the purposes of high-energy physics only at energies $E > 2 \times 10^{15}$ eV. Within about ten years, when the CERN LHC accelerator is put into operation, the energy E_c will increase by an order of magnitude, and we shall be able to speak about the use of cosmic rays only with an energy of $E > 10^{17}$ eV.

The highest particle energy recorded in cosmic rays is 3×10^{20} eV [42]. It may therefore seem that there are good reserves for the use of cosmic rays. Actually, this is not so because superhigh-energy particles are quite rare. According to [43], the intensity of particles with energy exceeding 10^{20} eV is on the order of one particle over a century per km^2 in a solid angle of one steradian. The intensity of particles with energy higher than 10^{18} eV is 60 particles/km$^2\cdot$sr $\cdot$ year while that of lower-energy particles naturally increases (roughly speaking, the integral intensity I is inversely proportional to E^2 at $E > 3 \times 10^{15}$ eV). But all the same, the intensity of cosmic rays seems to be too low to record isolated elementary collision events with $E > 10^{16}$–10^{17} eV. However, one may hope to indirectly obtain some information from extensive air showers. In any case, cosmic rays are still of interest to high-energy physics in the energy range exceeding 2×10^{15} eV.

4. Cosmic rays near the Earth. Estimation of the lifetime of cosmic rays and the power of their sources in the Galaxy

One of the main sources of information about cosmic rays is obviously the investigation of primary cosmic rays, that is particles observed outside the atmosphere. The measured quantity is differential intensity $I(E)$ or integral intensity

$$I(>E) = \int_E^\infty I(E)\, \mathrm{d}E,$$

where $I(E)\,\mathrm{d}E$ is the number of particles with energy in the range of $E + \mathrm{d}E$, E falling per unit surface in unit solid angle per unit time in the direction perpendicular to the surface. Thus, for example,

$$\left[I(E)\right] = \frac{\text{number of particles}}{\text{cm}^2 \cdot \text{s} \cdot \text{sr} \cdot \text{eV}}.$$

Because of cosmic ray isotropy (a very small degree of anisotropy is ignored), I does not depend on the angles. But, of course, I depends on the sort of particles, i.e. $I = I_{Z,A}$ for the proton-nuclear component (Z is the atomic number, A is the mass number) and $I = I_e = I_{e^-} + I_{e^+}$ for the electron-positron component. Summarised intensities

$$I_{\text{cr}} = \sum_{Z,A} I_{Z,A}, \qquad I_{\text{cr},Z} = \sum_A I_{Z,A},$$

are also used as well as fluxes through the hemisphere of directions

$$F_i = \int I_i\, \mathrm{d}\Omega = \pi I_i$$

(for isotropic radiation; Ω is the solid angle). The concentration of such particles with velocity v_i is

$$N_i = \frac{4\pi}{v_i} I_i,$$

and the energy density is

$$w_i = \int E_k N_i(E)\, \mathrm{d}E,$$

where $E_k = E - Mc^2$ is the kinetic energy. Also, it is possible to introduce the intensity of the energy flux

$$J_i = \int E_k I_i(E)\, \mathrm{d}E.$$

For primary cosmic rays near the Earth

$$I_{\text{cr}} \sim 0.2\text{–}0.3\ \frac{\text{particles}}{\text{cm}^2 \cdot \text{s} \cdot \text{sr}}, \quad N_{\text{cr}} \sim \frac{4\pi I_{\text{cr}}}{c} \sim 10^{-10}\ \frac{\text{particles}}{\text{cm}^3},$$
$$w_{\text{cr}} \sim 10^{-12}\ \frac{\text{erg}}{\text{cm}^3} \sim 1\ \frac{\text{eV}}{\text{cm}^3}, \quad J_{\text{cr}} \sim \frac{c w_{\text{cr}}}{4\pi} \sim 10^{-3}\ \frac{\text{erg}}{\text{cm}^2 \cdot \text{s} \cdot \text{sr}}, \tag{2}$$

where the velocity of cosmic rays particles is taken as $v \sim c$ because these particles are for the most part relativistic. Unfortunately, it is impossible to go into detail here, especially as regards modulation effects in the solar system. It should be noted that practically no primary particles reach the Earth's surface.

At sea level, that is, under the atmospheric layer of nearly 1,000 g/cm^2, only secondary cosmic rays are observed (about 70% of them are $\mu^\pm$-leptons (muons) and nearly 30% are electrons and positrons). For primary cosmic rays, the flux equals

$$F_{\text{cr}} = \pi I_{\text{cr}} \sim 1\ \frac{\text{particles}}{\text{cm}^2 \cdot \text{s}},$$

and at sea level $F \sim 10^{-2}$ particles/cm$^2\cdot$s.

A wealth of papers has been devoted to cosmic rays studies, and their number continues to grow. In other words, this is a vast field of research (see Ref. [33] and especially Ref. 41] for some data and references). But further discussion will be restricted to selected data and some comments.

The integral spectrum (intensity) of all cosmic rays in the energy range of $10^{10} < E < 3 \times 10^{15}$ eV is well described by the expression

$$I_{\text{cr}}(>E) = 1 \cdot \left[E\,(\text{GeV})\right]^{-1.7}\ \frac{\text{particles}}{\text{cm}^2 \cdot \text{s} \cdot \text{sr}}. \tag{3}$$

The influence of the solar system (heliosphere) is already noticeable at kinetic energies $\varepsilon_k \lesssim 10^{10}$ eV/nucleon, but we shall not touch upon this energy range. For energies $E > 3 \times 10^{15}$ eV:

$$I_{\text{cr}}(>E) = 3 \times 10^{-10} \left[\frac{E\,(\text{GeV})}{10^6}\right]^{-2}\ \frac{\text{particles}}{\text{cm}^2 \cdot \text{s} \cdot \text{sr}}. \tag{4}$$

There is a characteristic 'knee' (kink) in the spectrum at $E \sim 3 \times 10^{15}$ eV. Type (4) spectra hold for energies of up to

$E \sim 3 \times 10^{17}$–10^{18} eV. Afterwards, the spectrum changes [42]; the region of superhigh energies with $E > 10^{18}$ eV will be discussed at the end of this paper.

For the electron-positron component unseparated into electrons and positrons in the energy range $5 \times 10^9 < E < 10^{11}$ eV

$$I_e(>E) \equiv I_{e^-+e^+}(>E) = 1.5 \times 10^{-2} \left[E\,(\mathrm{GeV})\right]^{-2} \frac{\text{particles}}{\mathrm{cm}^2 \cdot \mathrm{s} \cdot \mathrm{sr}} . \quad (5)$$

The energy density for this component is

$$w_{\mathrm{cr},e} \sim 10^{-2} w_{\mathrm{cr}} \sim 10^{-14} \frac{\mathrm{erg}}{\mathrm{cm}^3} . \quad (6)$$

The number of positrons is around 10% of the total number of electrons and positrons, that is $I_{e^+} \sim 0.1 \cdot I_e$. Besides positrons, antiprotons were discovered in 1979, their number being by 3 – 4 orders of magnitude smaller than that of protons.

The chemical composition of cosmic rays has already been described. Fig. 1 shows that spectra for different nuclei are similar (they are distorted in the energy range of $\varepsilon_{\mathrm{k}} < 10^3$ MeV/nucleon as a result of solar modulation).

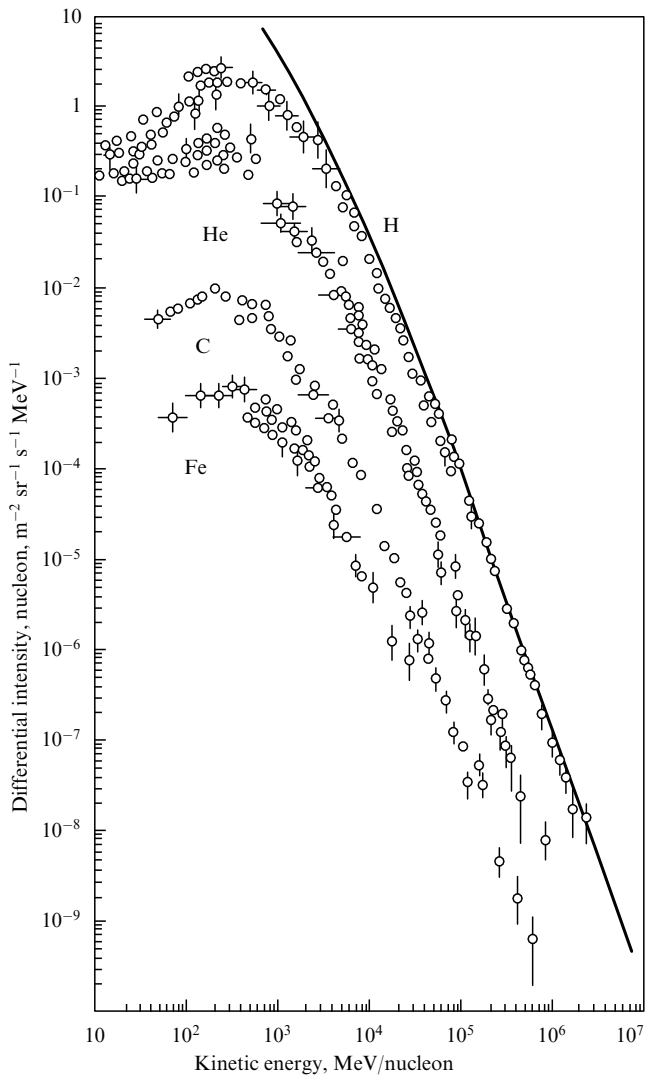

Figure 1.

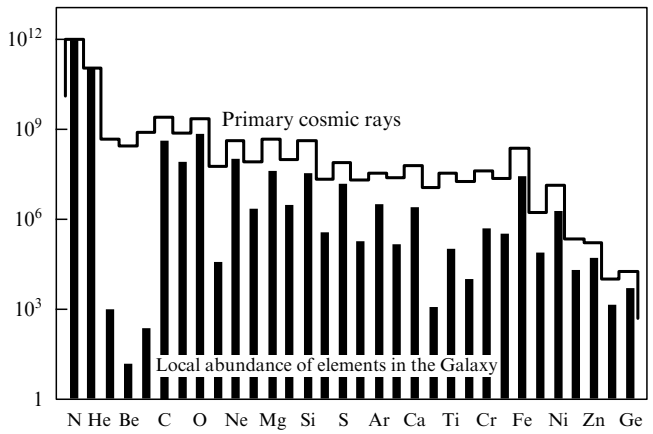

Figure 2.

Figure 2 presents the abundance of elements in the Galaxy and cosmic rays. Taken together, Fig. 2 and more comprehensive data indicate that, on the whole, the abundance of nuclei in cosmic rays reflects their concentration in outer space. For all that, there is some discrepancy especially pronounced as a marked difference in the distribution patterns of light elements: Li, Be, and B. The amount of these elements in cosmic rays is not much less than that of other elements, e.g. C, N, and O, in spite of their rare occurrence in nature. This and some other differences can be accounted for by the fact that cosmic ray nuclei wandering in interstellar space collide with atomic nuclei of interstellar gas (largely protons), which affects the cosmic ray composition. Specifically, transformation of heavier nuclei results in the production of Li, Be, and B nuclei. Analysis of available data on the chemical (elemental) and isotopic composition of cosmic rays [33] suggests the conclusion that interstellar gas thickness traversed by cosmic rays coming to the Earth, approximately equals $x \sim 5-10$ g/cm^2. On the other hand, it is evident that

$$x = v\rho\, T_{\mathrm{cr}} \approx c\rho\, T_{\mathrm{cr}} , \quad (7)$$

where $v \approx c$ is the velocity of particles in cosmic rays, and ρ and T_{cr} are the mean gas density and wandering time, respectively.

The interstellar medium is highly inhomogeneous. For this reason, values of density ρ in a cosmic ray trapping (occupation) region of the Galaxy cannot be deduced *a priori*. It will be shown below that there are grounds to believe that cosmic rays occupy rather a large halo with mean interstellar gas concentration $n \sim 10^{-2}$ cm^{-3} (largely composed of hydrogen and helium), which corresponds to the density $\rho \sim 2 \times 10^{-24}$ g·cm^{-3}. For such values of ρ and $x \sim 5-10$, one has

$$T_{\mathrm{cr}} \approx \frac{x}{c\rho} \sim 10^{14}\,\mathrm{s} \sim 3 \times 10^8 \text{ years.} \quad (8)$$

The power (luminosity) L_{cr} of cosmic ray sources in the Galaxy can be readily estimated as

$$L_{\mathrm{cr}} \sim \frac{w_{\mathrm{cr}} V}{T_{\mathrm{cr}}} \sim \frac{c w_{\mathrm{cr}} M_{\mathrm{g}}}{x} \sim 3 \times 10^{40} \frac{\mathrm{erg}}{\mathrm{s}} , \quad (9)$$

where $M_{\mathrm{g}} = \rho V \sim 5 \times 10^{42}$ g is the total mass of gas in the Galaxy (V is the volume), and the value given in (2) is used for the cosmic ray energy density w_{cr}; moreover, expression (7)

with $x \sim 5-10$ g·cm^{-2} is employed. Naturally, with such an estimate, the picture ought to be considered as quasi-stationary. It is of importance that the estimate (9) does not depend on the choice of a $T_{\rm cr}$ value and rests only on the observed quantities $w_{\rm cr}$, x, and $M_{\rm g}$.

Here, we have of course overstepped the limits of information about primary cosmic rays near the Earth and used the galactic model of cosmic ray origin. In this model, which is considered below, the majority of cosmic rays observed near the Earth are produced in our Galaxy and leave for the intergalactic space with the characteristic time $T_{\rm cr}$ (see (8)). Before leaving our Galaxy, cosmic rays roam in interstellar magnetic fields and lose a part of their energy; they essentially "drop out of the game".

5. Cosmic rays in the Universe

Direct information about cosmic rays travelling far from the Earth is obtained from observation of electromagnetic radiation produced by them in different frequency ranges. Of primary importance in this context are radioastronomy and gamma-astronomy. Some additional data are gathered in the optical and X-ray parts of the spectrum.

Fundamental principles of the theory of synchrotron radiation are fairly well known (see, for example, [32, 33, 44]), but it seems nonetheless necessary to recall some facts. A particle (of charge e and mass m) with the total energy E moves in a homogeneous magnetic field of strength $\mathbf{H}$ along a spiral with the angular frequency

$$\omega_H = \frac{|e|H}{mc}\,\frac{mc^2}{E} = 1.76\times 10^7\,H\,\frac{mc^2}{E}\,, \tag{10}$$

where, in passing to the last expression, the particles are electrons, and the field H is measured in oersteds (gausses). The same is true below. If the particle is ultrarelativistic, it emits waves in the direction of its own velocity within the angle on the order of mc^2/E. If the angle χ between $\mathbf{v}$ and $\mathbf{H}$ is not too small, i.e. $\chi \gg mc^2/E$, the particle emits waves with many frequencies which are overtones of $\omega_H/\sin^2\chi$. At $E \gg mc^2$, the spectrum is practically continuous, and the radiation intensity maximum corresponds to a frequency

$$\begin{aligned}\nu_{\rm m} \equiv \frac{\omega_{\rm m}}{2\pi} &= 0.07\,\frac{|e|H_\perp}{mc}\left(\frac{E}{mc^2}\right)^2 = 1.2\times 10^6 H_\perp\left(\frac{E}{mc^2}\right)^2\\ &= 1.8\times 10^{18} H_\perp\left[E\,({\rm erg})\right]^2\\ &= 4.6\times 10^{-6} H_\perp\left[E\,({\rm eV})\right]^2\ {\rm Hz}\,,\end{aligned} \tag{11}$$

$$\hbar\omega_{\rm m} = 1.9\times 10^{-20} H_\perp\left[E\,({\rm eV})\right]^2\ {\rm eV},$$

where $H_\perp = H\sin\chi$ is a component of the field $\mathbf{H}$ perpendicular to particle velocity $\mathbf{v}$.

In a typical interstellar field $H \sim H_\perp \sim 3\times 10^{-6}$ Oe for particles with the energy $E \sim 10^9 - 10^{11}$ eV, the frequency $\nu_{\rm m}$ falls in the range of $10^7 - 10^{11}$ Hz which corresponds to the wavelength $\lambda_{\rm m} = c/\nu_{\rm m} \sim 30$ m – 0.3 cm. Thus, the electron component of cosmic rays with $E > 10^9$ eV largely radiates in the radio-frequency range when in interstellar fields. At frequency $\nu_{\rm m}$, the spectral density of the radioemission power is

$$p_{\rm m} \equiv p(\nu_{\rm m}) = 1.6\,\frac{|e|^3 H_\perp}{mc^2} = 2.16\times 10^{-22} H_\perp\,\frac{\rm erg}{\rm s\cdot Hz}\,. \tag{12}$$

If we consider a region in which emitting electrons at a concentration $N_{\rm e}$ are isotropically distributed by velocity, the corresponding emissivity (the spectral power of radiation per unit volume and unit solid angle) is given by

$$\varepsilon_{\nu_{\rm m}} = \frac{p_{\rm m} N_{\rm e}}{4\pi} = 1.7\times 10^{-23} H_\perp N_{\rm e}\,\frac{\rm erg}{\rm cm^3\cdot s\cdot sr\cdot Hz}\,, \tag{13}$$

where $H_\perp$ is the mean value of a field component perpendicular to the particle velocity for the radiating volume. It is clear from Eqn (13) that the maximum radiation intensity for monochromatic electrons is

$$J_{\nu_{\rm m}} = \int \varepsilon_{\nu_{\rm m}}\,{\rm d}l = 1.7\times 10^{-23} H_\perp N_{\rm e} L\,\frac{\rm erg}{\rm cm^2\cdot s\cdot sr\cdot Hz}\,, \tag{14}$$

where L is the characteristic size of the region emitting radiowaves along the line of sight (i.e. $N_{\rm e}L = \int N_{\rm e}\,{\rm d}l$).

In the case of a discrete source of radioemission (e.g., a supernova remnant) which is at a distance R from us, the radiation flux (see (13)) is equal to

$$\Phi_{\nu_{\rm m}} = \frac{p_{\rm m} N_{\rm e} V}{4\pi R^2} = 1.7\times 10^{-23}\,\frac{H_\perp N_{\rm e} V}{R^2}\,\frac{\rm erg}{\rm cm^2\cdot s\cdot sr\cdot Hz}\,, \tag{15}$$

where V is the source volume.

According to expression (11), the electron energy $E = 0.75\times 10^{-9}\sqrt{\nu_{\rm m}/H_\perp}$ erg. From this and Eqn (15), it follows that the total electron energy in the source is

$$W_{\rm e} = E N_{\rm e} V = 4.4\times 10^{13}\,\frac{\nu_{\rm m}^{1/2}\Phi_{\nu_{\rm m}} R^2}{H_\perp^{3/2}}\,. \tag{16}$$

The radioemission flow $\Phi_{\nu_{\rm m}}$ can be measured directly, and it is easy to find $W_{\rm e}$ provided the values of R and $H_\perp$ for the source are known.

Unfortunately, the above expressions do not reflect the real situation because one does not normally deal with monoenergetic electrons in nature. It is often possible, however, to consider the electron spectrum as fairly simple, i.e. of the power-law type, when the concentration of electrons in the interval ${\rm d}E$ has the form

$$N_{\rm e}(E)\,{\rm d}E = K_{\rm e} E^{-\gamma_{\rm e}}\,{\rm d}E. \tag{17}$$

For this case, the intensity was also calculated [32, 33, 44] as follows:

$$J_\nu = {\rm const}\cdot K_{\rm e} L H^{(\gamma_{\rm e}+1)/2}\,\nu^{(1-\gamma_{\rm e})/2}, \tag{18}$$

where H is a certain average value of the magnetic field along the line of sight. It is clear from Eqn (18) that measuring the dependence of J_ν on frequency ν immediately yields index $\gamma_{\rm e}$ while the value of J_ν itself allows coefficient $K_{\rm e}$ to be determined if L and H are known, that is to find the electron spectrum in the source and then the associated energy density

$$w_{\rm cr,\,e} = \int E N_{\rm e}(E)\,{\rm d}E\,.$$

The dimensions of a radioemitting region, the distance R to discrete sources, and the volume V of these sources are determined by astronomical methods, in the first place from radio-observations. It is more difficult to determine the field H. Incidentally, one of the methods for measuring H is based on the same expression (18). Specifically, if the concentration

of relativistic electrons is assumed to be known (in fact, their number is supposed to be the same as that in primary cosmic rays near the Earth (see (5) and (6)), then the magnetic field H is estimated from the measured intensity J_ν, on the assumption that the dimension of the emitting region L along the line of sight is known (see (18)).

According to different estimates, in the Galaxy $H \sim 3 \times 10^{-6}$ Oe, which means that the density of cosmic ray energy (see (2)) is of the same order as the magnetic field density

$$w_{\rm cr} \sim w_H = \frac{H^2}{8\pi} \sim 10^{-12}\ \frac{\rm erg}{\rm cm^3}\,. \tag{19}$$

Such a situation must be expected in quasi-stationary conditions. Indeed, cosmic rays are 'frozen' in a well-conductive interstellar gas, and cosmic rays flow out of the region in question at $w_{\rm cr} \gg H^2/8\pi$, that is when cosmic ray pressure $p_{\rm cr} \approx w_{\rm cr}/3$ is higher than the magnetic field pressure. At $w_{\rm cr} \ll H^2/8\pi$, there is nothing to interfere with cosmic ray accumulation; therefore, the quasi-equilibrium state does not set in.

Generalisation of the relation (19) allows for the assumption that

$$\varkappa_H\, w_{\rm cr} = w_H, \qquad \varkappa_H W_{\rm cr} = W_H. \tag{20}$$

Here, $W_{\rm cr} = \int w_{\rm cr}\,{\rm d}v$ and $W_H = \int w_H\,{\rm d}v$ are the total energies of cosmic rays and the field in the volume being examined, respectively. Similarly, it is natural to assume that

$$\varkappa_{\rm e} w_{\rm cr,e} = w_{\rm cr} = \frac{w_H}{\varkappa_H}, \qquad \varkappa_{\rm e} W_{\rm cr,e} = W_{\rm cr}. \tag{21}$$

It has already been noted that near the Earth and in the Galaxy as a whole (see (19 and (6)),

$$\varkappa_H \sim 1, \qquad \varkappa_{\rm e} \sim 10^2. \tag{22}$$

If values of $\varkappa_H$ and $\varkappa_{\rm e}$ are given, one can find energies $W_{\rm cr,e}$, $W_{\rm cr}$, and W_H based only on the results of radio-observations. This is a frequently used procedure which leads to the conclusion (see, for example, [32]) that for supernova remnants, $W_{\rm cr} \sim 3 \times 10^{46}$–$5 \times 10^{49}$ erg. For normal galaxies and radiogalaxies $W_{\rm cr} \sim 10^{55}$–10^{57} erg and $W_{\rm cr} \sim 10^{58}$–10^{60} erg, respectively (it should be noted that 10^{60} erg is already $10^6\, M_\odot c^2$).

Given the value (19) and the characteristic volume occupied by cosmic rays $V_{\rm h} \sim 10^{68}$ cm^3, one finds that for our Galaxy

$$W_{\rm cr} \sim w_{\rm cr} V_{\rm h} \sim 10^{56}\,{\rm erg}. \tag{23}$$

The assumed value of $V_{\rm h}$ corresponds to a galactic halo with the characteristic size $h \sim 10$ kpc $\sim 3 \times 10^{22}$ cm. The very notion of the cosmic ray halo and the radio halo appeared in connection with the development of radio-astronomy because the 'optical' Galaxy is a disk with the characteristic half thickness $h_{\rm d} \sim 3 \times 10^{20}$ cm. Naturally, cosmic rays cannot be trapped in such a disk and, together with magnetic fields, form a halo. In the radio-frequency range, a radio halo may occur, that is the halo of the electron component of cosmic rays. Unfortunately, it is difficult to study the halo of the Galaxy from the Earth which is located inside the system. It is for this reason that the existence of the radio halo had long been a matter of dispute till 1977 when such a halo was first detected [45] by 'on-edge' observations of galaxies, in the first place NGC 4631 (see Fig. 3 in which black lines are isophots at a wavelength $\lambda = 49.2$ cm, i.e., at the frequency $\nu = 610$ MHz).

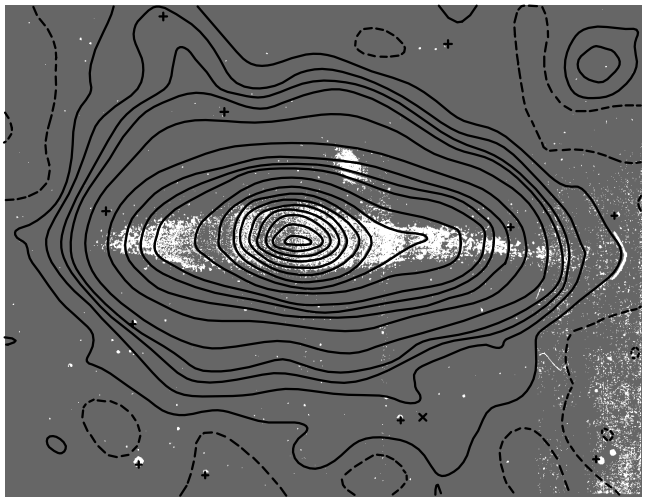

Figure 3.

Due to progress in radioastronomy, it has been demonstrated first that cosmic rays are a universal phenomenon, in that they are present in the interstellar space of our Galaxy, in nebulae (supernova remnants and others), in other galaxies, and especially in radiogalaxies and quasars. Second, it has been shown that cosmic rays occurring in the Universe collectively constitute an important energetic and dynamical factor. Specifically, their energy density is comparable to magnetic energy density, and their pressure is also high: $p_{\rm cr} \approx w_{\rm cr}/3$ (isotropic cosmic rays are dominated by relativistic particles). Furthermore, the energy density $w_{\rm cr} \sim 10^{-12}$ erg cm^{-2} is of the same order of magnitude as the energy density of relic thermal radiation with temperature 2.7 K. Generally speaking, the energy density of the interstellar gas

$$w_{\rm g} = \frac{3}{2}\, n k_{\rm B} T$$

is also of the same order of magnitude (for instance, at a gas concentration $n \sim 1$ cm^{-3} and temperature $T \sim 10^4$ K, $w_{\rm g} \sim 10^{-12}$ erg cm^{-3}).

These conclusions agree with the current views of plasma physics in that rarefied cosmic plasma particles must be accelerated in the presence of particle beams and shock waves. Cosmic rays are actually constituted by the 'tail' of particle energy distribution in outer space corresponding to high energy.

Of course, the synchrotron mechanism operates in all ranges, depending on the values of H and E. For example, $\nu_{\rm m} \sim 10^{15}$ Hz and $\lambda_{\rm m} = c/\nu_{\rm m} \sim 10^{-5}$ cm = 1000 A at $H_\perp \sim 10^{-3}$ Oe and $E = 10^{12}$ eV, respectively, in accordance with (11). Therefore, it is not surprising that in certain cases synchrotron radiation even of extended objects, such as Crab Nebula (a supernova remnant of 1054), also occurs in the optical and X-ray parts of the spectrum. Similarly, optical synchrotron radiation is observed in radiogalaxy Virgo A (galaxy NGC 4486). The synchrotron nature of radiation is

first of all apparent from polarisation. The point is that synchrotron radiation can be highly polarised. For instance, synchrotron radiation of an individual electron is in general elliptically polarised, the value of the electric vector of radiation being maximal in the direction of acceleration. For this reason, the prevailing direction of oscillations is perpendicular to the projection of the magnetic field ($\mathbf{H}_\perp$) onto the plane perpendicular to the line of sight. If the magnetic field in a radiation source was on the average chaotic in terms of direction, polarisation would be absent. Actually, however, it is frequently observed, which suggests the presence of an ordered field (see [32] for more details).

The so-called curvature radiation related to synchrotron radiation is especially efficient in pulsars when fields attain values $H \sim 10^{12}$–10^{13} Oe. In the first approximation, curvature radiation can be described by the formulae which are known to hold for synchrotron radiation, provided the Larmor radius r_H is substituted by the field-line curvature radius R_H. In this case, relativistic electrons with available energy in fields with $H \sim 10^{12}$ Oe emit very hard gamma-rays. Pulsars produce gamma-radiation which is most likely to be curvature radiation of electrons and positrons accelerated in the vicinity of pulsars, i.e. magnetised and rotating neutron stars.

Also, gamma-ray emission with the continuous spectrum is generated by relativistic electrons as a result of Bremsstrahlung and the inverse Compton effect against the background soft electromagnetic radiation, i.e. microwave radiation with temperature 2.7 K as well as optical and infrared radiation. However, these mechanisms cannot be discussed here at greater length (see, for example, [33, 44]). Of special interest from the standpoint of cosmic ray astrophysics is the aforementioned gamma-ray emission generated by the proton-nuclear component of cosmic rays as a result of collisions with gas nuclei leading to the formation of π^0-mesons and some other particles which rapidly decay and give rise to gamma-photons. The importance of such gamma-ray emission is evident: it directly provides information about the proton-nuclear component, without any additional assumption being needed to connect it with the electron component (see (21)).

The decay of π^0-mesons (mean lifetime of 0.84×10^{-16} s) with the probability of 98.8% proceeds along the channel $\pi^0 \to 2\gamma$. For this reason, decay of a π^0-meson at rest generates gamma-photon with energy

$$E_\gamma = \frac{m_{\pi^0} c^2}{2} = 67.5 \text{ MeV}\,.$$

Other reactions and decays which result in the formation of gamma-rays, e.g. $\Sigma^0 \to \Lambda + \gamma$ decay, are not so important and we do not mention them for simplicity.

The intensity of gamma-rays thus produced is proportional to the nuclei concentration n in a gas (in interstellar space or, say, in a supernova remnant) and to the cosmic ray intensity $I_{\rm cr}$. Specifically, the differential intensity of gamma-rays in terms of the photon number (the gamma-ray spectrum) along the line of sight is equal to

$$I_\gamma(E_\gamma) = \int \sigma(E_\gamma,\, E)\, n(l)\, I_{\rm cr}(E,\, l)\, \mathrm{d}l\,, \tag{24}$$

where $\sigma(E_\gamma,\, E)$ is the corresponding effective cross-section for the formation of gamma-rays with energy E_γ by cosmic rays with energy E (certainly, the cross-section should be averaged taking into account the elemental and isotopic composition of both cosmic rays and nuclei in the gas).

The following equation for a gamma-ray flux from a discrete source based on expression (24) is obtained:

$$F_\gamma(>E_\gamma) = \int_\Omega I_\gamma(>E_\gamma)\, \mathrm{d}\Omega = \frac{\overline{(\sigma I_{\rm cr})}\, \tilde{n}(V)}{R^2}\, \frac{\text{photons}}{\text{cm}^2 \cdot \text{s}}\,, \tag{25}$$

where Ω is the solid angle at which the source is viewed at a distance R, $\overline{(\sigma I_{\rm cr})}$ is the cross-section averaged over the cosmic ray spectrum, and $\tilde{n}(V)$ is the number of gas nuclei in a source of volume V.

Unless studying cosmic gamma-rays with energy $E > 10^{11}$–10^{12} eV on the Earth's surface by their optical Vavilov–Cherenkov radiation in the atmosphere, heavy satellites have to be used to receive gamma-ray emission. But launching such gamma-ray observatories is a difficult task. There have been only three of them during the whole history of gamma-astronomy , viz. satellites SAS II (1972 – 1973), COS-B (1975 – 1982, E_γ >30 – 70 MeV), and the currently-operating Compton Gamma-Ray Observatory (CGRO) launched in April 1991. CGRO carries instruments independently functioning in various parts of the gamma-ray spectrum. Here, we are interested in the operation of the EGRET apparatus which receives gamma-rays with $E_\gamma > 30$–50 MeV, i.e. it records in particular gamma-rays resulting from the π^0-meson decay.

It will not perhaps be out of place to emphasise that the magnitude of high-energy cosmic gamma-ray fluxes is fairly small. For instance, for the powerful galactic source (pulsar) Geminga, $F_\gamma(>E_\gamma = 100\,\text{MeV}) = 4.8 \times 10^{-6}$ photons cm^{-2} s^{-1}. Such a flux is by six orders of magnitude smaller than the primary cosmic ray flux near the Earth (see (2)). For this reason, gamma-astronomical studies are very difficult to perform especially at higher energies. As a result, not a single gamma-ray observatory was running between 1982 and 1991, and it is only CGRO that is currently in operation.

It is, of course, impossible to discuss here in any detail results of gamma-astronomical studies even in the high-energy range of $E_\gamma > 30$–50 MeV. We shall only mention the enormous luminosity of certain gamma-ray sources. For example, galactic sources (pulsars, molecular clouds, etc.) have luminosity $L_\gamma \sim 10^{34} - 10^{36}$ erg/s which can be defined, based on the flux measurements, by the expression

$$L_\gamma = 4\pi R^2 \int E_\gamma F_\gamma\,(>E_\gamma)\, \mathrm{d}E_\gamma\,, \tag{26}$$

that is, on the assumption of isotropic nature of the emission (4π factor); luminosity is certainly weaker if the emission is not isotropic. If, for example, $F_\gamma(>E_\gamma = 100\text{ MeV}) \sim \sim 5 \times 10^{-6}$ photons/cm$^2 \cdot$ s for the spectrum $F(>E_\gamma) \sim E_\gamma^{-2}$, then $L_\gamma \sim 10^{35}$ erg/s at the distance $R = 1000$ pc $\sim 3 \times 10^{21}$ cm. Specifically, for the Crab (pulsar PSR 0531), $L_\gamma(50\text{ MeV} < E_\gamma < 10\text{ GeV}) \approx 2 \times 10^{35}$ erg/s. The total gamma-ray luminosity of our Galaxy $L_\gamma(>70\text{ MeV}) \sim \sim 10^{39}$ erg/s which corresponds to approximately 2×10^{42} photons/s for the observed spectrum. For quasar 3C 279 which is at a distance $R \sim 5000$ Mpc, the EGRET apparatus has shown the highest value ever recorded: $L_\gamma(50\text{ MeV} < E_\gamma < 3\text{ GeV}) \sim 10^{48}$ erg/s. For the known quasar 3C 273, $L_\gamma(50\text{ MeV} < E_\gamma < 0.5\text{ GeV}) \simeq 2 \times 10^{46}$ erg/s (the distance is assumed to be $R = 790$ Mpc). The total luminosity of this quasar is unlikely to exceed the value of

$L = (2-5) \times 10^{47}$ erg/s, and its X-ray luminosity L_X (0.5 keV $< E_X <$ 4.5 keV) $\approx 1.7 \times 10^{46}$ erg/s. It is worthwhile recalling that the total (largely optical) luminosity of the Sun $L_\odot = 3.8 \times 10^{33}$ erg/s, and that of the Galaxy $L_G \sim 10^{44}$ erg/s. By the way, the total luminosity of the Galaxy in the radio-frequency range is $L_{G,rf} \sim 3 \times 10^{38}$ erg/s.

Since high-energy gamma-rays are produced by cosmic rays, it is quite clear from the above considerations that cosmic rays must play an important role in the Universe.

6. The origin of cosmic rays

In a broad context, the problem of the origin of cosmic rays is the problem of their acceleration and propagation under various conditions. However, the discussion of this problem is usually limited to cosmic rays observed near the Earth and in the solar system. Such cosmic rays are certainly different from others in that a large amount of information about them is available directly by physical methods. It is in this context that the origin of cosmic rays will be discussed below. Soft cosmic rays of solar origin are not included in the discussion because their contribution to the total cosmic radiation near the Earth with $\varepsilon_k \gtrsim 10^8$ eV/nucleon is very small. The same is true of superhigh-energy cosmic rays ($E \gtrsim 10^{17}$ eV) which will be considered in the next section.

As regards the origin of the bulk of cosmic rays observed near the Earth, one should answer the following questions:

What is the region occupied by these cosmic rays?

How do they propagate and what transformations do they undergo in the interstellar medium?

What are their sources?

What is the mechanism of their acceleration?

In the past, three models of cosmic ray origin were suggested, usually referred to as solar, galactic, and metagalactic theories. The solar, or local model, assumed cosmic rays to originate in the Sun and occupy the heliosphere. According to this theory, other stars may just as well serve as sources of cosmic rays, although cosmic rays are sparse in the galactic space. However, this standpoint could seem worthy of serious note only as long as the association between cosmic rays and cosmic radioemission remained obscure [27 – 31], that is until 1953 (true, the theory was even later advocated by certain authors [5]). But since it became clear that cosmic rays are more or less uniformly distributed across the entire Galaxy, the local model of cosmic ray origin has no longer been considered valid (actually, it appears to be irrelevant even despite of radioastronomical data).

In compliance with galactic models, cosmic rays are supposed to originate and concentrate in the Galaxy from which they can flow out into metagalactic space. Finally, metagalactic models postulate that cosmic rays occupy the entire Metagalaxy from which they flow into the Galaxy. In the context of the latter models, in order that cosmic rays in the Galaxy and especially near the Earth should mostly be of metagalactic origin, it is necessary that their concentration, spectrum, and energy density w_{cr}^M in the vicinity of the Galaxy be the same as the corresponding characteristics of primary cosmic rays near the Earth. This means that in the metagalactic models

$$w_{cr}^M \approx w_{cr}^G \equiv w_{cr}\,, \tag{27}$$

where $w_{cr} \sim 10^{-12}$ erg/cm^3 is the aforementioned energy density of cosmic rays near the Earth (see (2)).

The energy density (27) is very high, and it is rather difficult to obtain such a value (evidently, it can be achieved, if ever, due to the generation processes in galaxies including radiogalaxies and quasars). This constitutes, so to speak, an energetic objection to the metagalactic theory (see, for example, [32]). Nevertheless, it was supported by some authors not very long ago [46].

Direct arguments were needed against the metagalactic models. They seem to be available now. After relic thermal radioemission with temperature 2.7 K was discovered in 1965, it became clear that the entire space is occupied by microwave radiation with the corresponding energy density being $w_{ph,T} = 4 \times 10^{-13}$ erg/cm^3. In addition, there are many optical and infrared photons in space. Relativistic electrons travelling in magnetic and radiation fields undergo energy losses due to synchrotron radiation and the inverse Compton effect, in proportion to the energy density $H^2/8\pi + w_{ph}$, where radiation energy density $w_{ph} > w_{ph,T}$. On the whole, the intergalactic magnetic field is likely to be rather weak ($H < 10^{-7} - 10^{-8}$ Oe), but the inverse Compton loss is equivalent to synchrotron losses in a field $H_{eqv} = \sqrt{8\pi w_{ph}} \gtrsim 10^{-6}$ Oe. Therefore, it is clear (see, for instance, [33]) that relativistic electrons with $E > 10^{10}$ eV and probably even $E > 10^9$ eV could not reach the Earth even from the nearest radiogalaxy Centaurus A (the distance $R \approx 4$ Mpc). Furthermore, travelling electrons would generate an inadmissibly strong X-ray and gamma-ray emission due to the inverse Compton effect. This indicates that the electron component of cosmic rays present in the Galaxy must take its origin in the Galaxy itself.

For this reason, it would be inappropriate to believe that the proton-nuclear component comes from other galaxies [46]. Irrelevance of metagalactic models immediately follows from gamma-astronomical observations. Indeed, in the framework of the metagalactic theory one can predict, based on relation (27), the presence of a gamma-ray flux generated by the proton-nuclear component in Magellanic Clouds [40, 47, 48]. For example, in the Small Cloud

$$F_\gamma^{SMC}\,(> E_\gamma = 100\ \text{MeV}) = (2-3) \times 10^{-7}\ \frac{\text{photons}}{\text{cm}^2 \cdot \text{s}}\,. \tag{28}$$

However, CGRO measurements provide the estimate [49]:

$$F_\gamma^{SMC}\,(> E_\gamma = 100\ \text{MeV}) < 0.5 \times 10^{-7}\ \frac{\text{photons}}{\text{cm}^2 \cdot \text{s}}\,. \tag{29}$$

Therefore, the following inequality holds even if with a rather small reserve:

$$w_{cr}^M \ll w_{cr}\,, \tag{30}$$

which is in conflict with the metagalactic theory.

Gamma-astronomical measurements of the cosmic ray concentration (density) gradient in the Galaxy [50] might just as well serve the same purpose. Unfortunately, the corresponding COS-B findings are not sufficiently accurate, and the CGRO data are as yet unavailable.

It follows from the above that the metagalactic theory is unacceptable, and only galactic models deserve consideration (rather than a model because the cosmic ray distribution over the Galaxy can be different, etc.). The basic difference between galactic models is that between galactic disk and galactic halo models. In the galactic disk models, cosmic rays are assumed to be concentrated within a certain galactic disk with the characteristic half thickness h_d which is much less

than the disk radius or, say, the distance between the Sun and the centre of the Galaxy $R \sim 3 \times 10^{22}$ cm. On the contrary, according to the galactic halo models, cosmic rays form (fill up) a halo, that is a quasi-spherical or a somewhat flattened region surrounding the stellar Galaxy (the Milky Way) with the characteristic dimension (radius) $h \sim 3 \times 10^{22}$ cm. We have already discussed the galactic halo models which are supported by both physical considerations and radio-astronomical data. As far as the disk models are concerned, there is no evidence in their favour, and they do not appear to have any advantage except for simplicity of some calculations on the assumption that cosmic rays are uniformly distributed over a certain disk (the so-called 'leaky-box' model).

Some parameters of the galactic halo model have already been discussed (see (8), (9), (23)). Now, we present them together for the sake of convenience.

Dimensions of the cosmic ray halo $h \sim (3-5) \times 10^{22}$ cm = 10–15 kpc. The radio halo is somewhat smaller; its characteristic dimension depends on the observed radio-emission frequency, i.e. electron energy, and increases with decreasing frequency.

Volume $V_{\rm h} \sim 10^{68}$ cm^3.

Total cosmic ray energy $W_{\rm cr} \sim w_{\rm cr} V_{\rm h} \sim 10^{56}$ erg $\sim 100\, M_{\odot} c^2$.

Total energy of the electron component $W_{\rm cr,e} \sim 10^{-2}\, W_{\rm cr} \sim 10^{54}$ erg.

Characteristic lifetime of cosmic rays (protons) in the Galaxy (within the halo) $T_{\rm cr} \sim (1-3) \times 10^8$ years $\sim (3-10) \times 10^{15}$ s.

Power (luminosity) of cosmic ray sources $U_{\rm cr} \equiv L_{\rm cr} \sim W_{\rm cr}/T_{\rm cr} \sim (1-3) \times 10^{40}$ erg/s.

Power of electron component sources $U_{\rm cr,e} \sim W_{\rm cr,e}/T_{\rm cr,e} \sim 10^{39}$ erg/s.

Here, it is taken into account that the characteristic lifetime of electrons $T_{\rm cr,e}$ is less than $T_{\rm cr}$ because electrons undergo losses due to synchrotron radiation and the inverse Compton effect. The time $T_{\rm cr}$ has been estimated above (see (8)). A similar result is obtained when calculations take into consideration cosmic ray diffusion, which is responsible for their departure from the halo [33]. Unfortunately, we cannot discuss at greater length the diffusion and transformation of the chemical composition of cosmic rays during their propagation in galactic magnetic fields. The same is true of the cosmic ray acceleration mechanism. These issues have been discussed extensively in many papers cited in reviews [32, 33, 51, 52] and in [41].

But one problem, namely that of the cosmic ray sources in the Galaxy, cannot be avoided even in the present paper which is by no means intended for specialists.

Since the Sun generates cosmic rays, especially during solar flares, it is natural to believe that other stars can also serve as cosmic ray sources. But the mean power of cosmic ray generation by the Sun is $L_{\rm cr,\odot} \sim 10^{24}$ erg/s (see Ref. [53] which reports the generation power $q_{\rm cr,\odot} \sim 10^{26}$ s^{-1} in terms of the number of particles; one arrives at the same $L_{\rm cr,\odot}$ value by assuming the mean particle energy to be 10^{10} eV $\sim 10^{-2}$ erg).†

† This estimate is incorrect. The author is grateful to L I Dorman for his report that median luminosity of the Sun in cosmic rays is $L_{\rm cr,\odot} \sim 10^{25}$ erg/s, with soft rays of $E_{\rm k} > 10$ MeV being predominantly emitted. Hence, the total luminosity of all 'ordinary' stars in the Galaxy $L_{\rm cr} \sim 10^{36}$ erg/s. In other words, ordinary stars can ensure neither the necessary power of cosmic ray generation in the Galaxy, nor their acceleration to energies $E > 10^9 - 10^{10}$ eV.

That is why it may be supposed that even all the 10^{11} stars in the Galaxy taken together cannot account for the power of more than $L_{\rm cr} \sim 10^{35}$ erg/s instead of the necessary power (1–3)$\times 10^{40}$ erg/s. Of course, some stars are much more active than the Sun, but there are not many of them. Therefore, it is hard to believe that ordinary stars serve as the main source of cosmic rays. On the contrary, there is every reason to suppose that such sources may be supernova flares. This hypothesis was first suggested by Baade and Zwicky as far back as 1934 [54].

During a supernova flare, the energy $W_{\rm SN} \sim 10^{49}$–10^{51} erg is released in the form of kinetic energy and radiation (while the neutrino energy amounts to $W_{{\rm SN},\nu} \sim 10^{53}$ erg which is the case, for example, with supernova SN 1987A). The average time between supernova flares in the Galaxy is assumed to be $t_{\rm SN} \sim 30$ years. From this, the mean power corresponding to supernova flares is

$$L_{\rm SN} \sim \frac{W_{\rm SN}}{t_{\rm SN}} \sim 10^{40} - 10^{42}\ \frac{\rm erg}{\rm s}. \tag{31}$$

Because supernovae may be of different types and only rough estimates of $W_{\rm SN}$ and $t_{\rm SN}$ are available, the value (31) is also approximate. There are no other equally powerful energy sources in the Galaxy. Furthermore, radio-astronomical observations provide evidence of rather strong radioemission from supernova remnants which unambiguously suggests the presence of relativistic electrons in them. Results of usual calculations based on the assumption (22) indicate that supernova remnants contain the proton-electron component with $W_{\rm cr,SN} \sim 3 \times 10^{46} - 5 \times 10^{49}$ erg [32]. But cosmic rays leave the remnants whereas acceleration by shock waves occurs both inside and outside the remnants. For this reason, the energy transferred to cosmic rays during a flare may be as high as $W_{\rm cr,SN} \sim 10^{49} - 10^{50}$ erg. This means that an estimate like (31) readily yields the required power $L_{\rm cr} \sim (1-3) \times 10^{40}$ erg/s for $L_{\rm cr,SN}$. We believe that collectively all these arguments leave no doubt that supernova flares are the main cosmic ray sources in the Galaxy. Additional information on this subject is likely to be obtained by gamma-astronomical techniques including observations of gamma-rays from supernova remnants and their neighbourhoods [51, 52, 55, 56]. Meanwhile, we do not see any real ground to consider our conclusion about the role of supernovae to be unconvincing [56] before such measurements are made. However, this does not at all mean that generation of cosmic rays by stars (especially by novae, OB stars, and some others) is of no interest. On the contrary, this is one of the most important problems (see, for example, [57]).

7. Superhigh-energy cosmic rays. Concluding remarks

We have traced the progress in cosmic ray studies from the beginning of this century. Amazing is the grandeur of the efforts made and the results obtained. Simple measurements of 'dark' current in ionisation chambers in early studies gave way to investigations with a variety of sophisticated instruments used both on the Earth and on heavy satellites. It is not at all an easy task to adequately describe the achievements and to characterise the modern state of cosmic ray astrophysics. It is not for the author to judge to what extent he has reached this goal. However, it may be hoped that at least one

thing is clear: the place of cosmic ray astrophysics in modern astronomy is similar to that of radioastronomy and gamma-astronomy. All these fields are closely related and develop jointly.

Coming back to the history, it is worthwhile to note that even about forty years ago (especially thirty years ago [32]), the use of radio-astronomical data allowed the following inferences to be drawn (here, it will be necessary to reiterate what has already been stated previously).

Cosmic rays are a universal phenomenon and play an important energetic and dynamical role in the Universe.

The bulk of cosmic rays observed near the Earth are of galactic origin and fill up the galactic halo (the galactic halo model).

The basic cosmic ray sources in the Galaxy are supernovae.

Some elements of this picture had long remained hypothetical but were all fully confirmed later. For instance, the long-standing controversy concerning the existence of radio halo was practically settled in 1977 [45]. The metagalactic models were finally invalidated after the discovery of relic radiation (1965) and the measurements of gamma-ray flux from Magellanic Clouds (1993; see [48, 49]). Also, a significant achievement was the elucidation (in 1977 – 1978) of the mechanism of diffusional acceleration of particles in shock waves (for references to original papers see [33, 52]).

To summarise, we believe that now the problem of cosmic ray origin may with a high degree of approximation be considered as a solved one excepting that of superhigh-energy cosmic rays. More precisely, the situation is fairly clear in the range of energies lower than $E \sim 3 \times 10^{15} - 3 \times 10^{16}$ eV, i.e. beneath the 'knee' (see (4)). Moreover, there is little doubt that it is possible to effectively accelerate particles in interstellar space by shock waves from supernovae (see, for instance, [56] and also [58] as well as the literature cited therein). True, supernovae (including pulsars) can in principle provide acceleration to substantially higher energies, but this requires additional assumptions [33, 51, 58]. The origin of the 'knee' has not yet been fully clarified; besides, there are a number of unsolved problems in the energy range above the 'knee' [59]. This is especially true of the energy range $E \gtrsim 3 \times 10^{18}$ eV. The point is that there is another break in the cosmic ray spectrum for the energy $E \sim 3 \times 10^{18}$ eV [42] (see Fig. 4). One is led to believe that a certain new cosmic ray component begins to dominate at $E > 3 \times 10^{18}$ eV. It is natural to think that this component is of metagalactic origin. Indeed, it is very hard (although possible) to accelerate such particles in the Galaxy, whereas such energies are rather easily attainable in radio-galaxies and quasars (active galactic nuclei) [33, 58]. Moreover, there is another difficulty as regards this case: protons, to say nothing about nuclei, cannot freely propagate in intergalactic space. The thing is that during collisions with photons of relic radiation ($T = 2.7$ K) or with infrared and optical photons, the nuclei undergo splitting and the protons are decelerated due to the production of e^+e^- pairs, followed by π-mesons, etc. As a result, the spectrum must steepen sharply (see [33] and the references to original literature thereof). Specifically, a proton with the highest observed energy of 3×10^{20} eV [42] cannot have a lifetime longer than 10^8 years or so. In other words, it cannot come from a distance exceeding approximately 10^{26} cm $\sim$ 30 Mpc. At the same time, particles with such an energy do not practically deviate in galactic and intergalactic magnetic fields, and therefore the direction to the source is known. But there is no visible source in this direction [60, 61]. The same is true of other rare events with $E \gtrsim 10^{20}$ eV. Thus, the problem of the sources of superhigh-energy cosmic rays remains to be elucidated. It has been even hypothesized [61] that these sources are the so-called topological defects which probably arose at early stages of cosmological evolution.

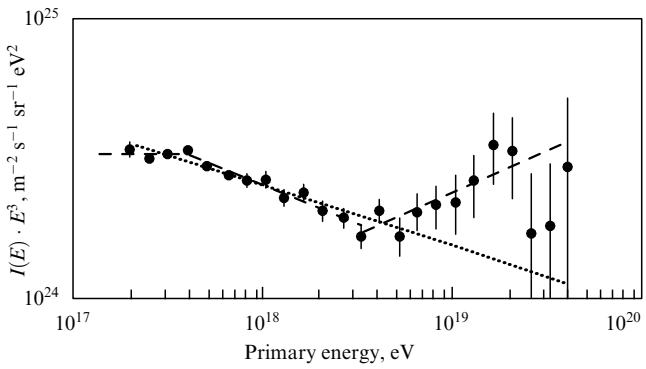

Figure 4.

These remarks are fragmentary and pursue only one goal: to show that the priority area of cosmic ray studies has now moved towards super-high energy cosmic rays. It is only in this energy range that fundamental uncertainties still remain and real discoveries can be anticipated. Of course, this statement may seem speculative, but it appears quite reasonable to pay special attention to the exploration of superhigh-energy cosmic rays. Specifically, projects for the construction of new large-area installations to observe extensive air showers look very promising [41, 59]. It is desirable that the energy, the direction of arrival, and the charge be established for each primary particle.

Another topical line of research is the detection of cosmic neutrinos with energies exceeding approximately 10^{12} eV, which may contribute to the establishment of high-energy neutrino astronomy [33, 34, 62]. The sources of such neutrinos are cosmic rays; hence, the close links between high-energy neutrino astronomy and cosmic ray astrophysics similar to those with gamma-astronomy are obvious. Such co-operation will in all probability prove to be very fruitful. At present, four installations for the observation of high-energy neutrinos are under construction [34]. Results may be expected in the near future.

8. Appendix

Cosmic ray astrophysics is currently a very broad area of research closely related to a variety of scientific disciplines, such as gamma and X-ray astronomy, radioastronomy, nuclear physics, high-energy physics, physics of the Sun, etc. For this reason, it was impossible even to mention many problems pertaining to cosmic ray astrophysics in the present paper, no matter how lengthy it may seem. It is therefore worthwhile to briefly review the materials of the 24th International Cosmic Ray Conference (24th ICRC) held in Rome from August 28 to September 8, 1995.† The review will be accompanied with comments on current problems and on-going research.

† A similar review of the 20th ICRC (Moscow, 1987) was published in [63]. These conferences are biennial.

8.1 The 24th International Cosmic Ray Conference

The number of participants at the Conference amounted to 800 persons, who presented around 1,100 reports. Four volumes of nearly 4,000 pages containing materials of the Conference were issued by its opening. Two of them (volumes 2 and 3) were largely devoted to the origin of cosmic rays (designated as the OG problem). All communications on this problem were grouped as follows:

1. X-Ray. Observations.
2. X-Ray. Theories and Models.
3. X-Ray. Techniques.
4. Gamma-Ray Bursts. Observations. Low Energies.
5. Gamma-Ray Bursts. Observations. High Energies.
6. Gamma-Ray Bursts. Theories and Models.
7. Gamma-Ray. Galactic Source Observations.
8. Gamma-Ray. Diffuse and Extragalactic Source Observations.
9. Gamma-Ray. Theories and Models.
10. Crab Observations.
11. Gamma-Ray. Search and Observations of Gamma-Ray Sources.
12. Extragalactic Gamma-Ray Sources.
13. Gamma-Ray. Techniques.
14. Cosmic Ray Composition. Low Energy.
15. Cosmic Ray Isotopic Composition. Low Energy.
16. Cosmic Ray Spectra. Low Energy.
17. Cosmic Ray Composition. High Energy.
18. Cosmic Ray Spectra. High Energy.
19. Cosmic Ray Anisotropy. High Energy.
20. Electrons and Positrons Intensity and Spectra.
21. Electrons and Positrons Origin and Propagation.
22. Antiprotons and Antinuclei.
23. Cosmic Ray Propagation.
24. Nuclear Interaction Cross Sections.
25. Shock Acceleration of Cosmic Rays.
26. Cosmic Ray Transport.
27. Origin of UHE Cosmic Rays.
28. Supernovae and Sources of Cosmic Rays.
29. Cosmic Ray Origin and Source Composition.
30. Cherenkov Telescopes.
31. Air Showers Arrays.
32. Balloon Instrumentation.
33. Miscellanea.
34. Computing and DAQ.
35. General Astrophysics.
36. Physical Processes.

Because space is limited, the contents of volumes 1 (HE — the nuclear aspect of cosmic ray physics) and 4 (SN — cosmic rays from the Sun and in the heliosphere) will not be discussed here at full length. We must note, however, that the distribution of the materials by volumes is somewhat arbitrary. For example, volume 1 contains many reports on extensive air showers (EAS) and devices for the observation of gamma-rays in EAS, together with the results obtained on accelerators, e.g., those concerning fragmentation of nuclei. Much attention is given to muon and neutrino studies (including those on atmospheric neutrinos and cosmic neutrinos with high and superhigh energies) and projects for the construction of necessary observing facilities.

Volume 4 contains data on solar radiation in X-ray and gamma-ranges, generation of various particles on the Sun, and solar neutrinos. Also, different aspects of particle propagation and acceleration in the heliosphere are highlighted, along with a number of other problems.

In addition to these reports, a few lectures were delivered at the Conference by invited speakers who actually reviewed recent progress in most topical research:

1. Prospects and Results of Gamma-Astronomy Using EAS.
2. Gamma-Ray Bursts.
3. Solar Neutrinos.
4. Supernovae.
5. Paleoasrophysics and Cosmic Rays.
6. Astroparticle Physics.
7. Compton Gamma-Ray Observatory (CGRO).
8. Antimatter in the Universe.
9. The History of Cosmic Ray Discovery and Investigations.

'Special sessions' were devoted to terrestrial gamma-astronomy, effects of solar events and processes in the heliosphere on man and his surroundings, the Ulysses mission (a space probe flown to make measurements beyond the ecliptic plane), and interactions in cosmic rays with superhigh energy. Finally, 10 workshops were organised to discuss a wealth of other problems. At the end of the Conference, 11 reporter talks were presented. In a word, all the ten working days of the Conference proved to be very busy, and several sessions had to be run in parallel to cover the programme.

Reviews and reporter talks as well as the materials of 'special sessions' will later be published in the Nuovo Cimento.

The 25th ICRC will take place in South Africa in 1997.

It is worth mentioning that a number of minor conferences and workshops are being held in-between the biennials, which raise issues of immediate relevance to narrower circles of specialists. Nevertheless, large regular meetings like ICRC turn out to be of great value, each contributing to the further development of science.

8.2 Comments

It should be noted that my paper traces the progress of cosmic ray studies only up to the early 1950s when cosmic ray astrophysics actually arose. For recent developments in this discipline, the reader is directed to current review papers. This accounts for the absence of a reference even to the work of Fermi [64], which actually initiated studies on particle acceleration in space plasma as far back as 1949.

The present paper emphasises how important it is today to study cosmic rays with superhigh energies of $E > 10^{15} - 10^{16}$ eV. This goal can in the first place be attained using instrumentation for detecting EAS, and its modification and improvement should be regarded as a most challenging task. In this context, the Russian project of an installation with the surface of 1,000 sq km (leader G B Kristiansen) [59], (see also Ref. [41b], Vol. 1, p. 466) should be mentioned as well as an international project [65] that envisages the construction of a device with a total surface of 5,000 sq km (more precisely, two such devices in the Southern and Northern hemispheres, respectively, with J Cronin and A Watson as leaders). For comparison, the EAS recording devices currently available are distributed over the surface of not more than 100 sq km each.

The so-called 'knee' (kink) in the cosmic ray spectrum mentioned earlier in this paper occurs in the energy range of 10^{15}–10^{16} eV. This 'knee' is most often associated with the conditions of cosmic ray propagation in the Galaxy or the process of their acceleration in the sources. However, accord-

ing to a different point of view [66], the 'knee' may be due to an energy-dependent change in the process of particle formation, which accompanies showers generated in the atmosphere on collision between the primary nucleus and atmospheric nuclei. By sheer coincidence, this 'knee' falls exactly within the energy range in which modern high-energy accelerators 'won't work' (see above formula (1) in the paper). Therefore, the only way to verify this hypothesis is to continue measurements either directly in cosmic rays or on the LHC accelerator which is due to come into operation at the beginning of the next century.

Clearly, there is no way even to mention all data reported at the 24th ICRC because great progress has been made in all priority areas of research. For all that, it is safe to conclude that no radically new data have recently been obtained that might change the picture presented in this paper.

CGRO is still functioning, and data processing is underway. The nature of gamma-ray bursts remains obscure, and novel information about cosmic rays in the Galaxy is needed.

In 1983, gamma-astronomy seemed to be on the brink of an important discovery when gamma-radiation of certain cosmic sources (in the first place, that of Cyg X-3) was reported to have energy in excess of 10^{14}–10^{15} eV. These data were experimentally tested using different devices: in some cases they were confirmed, but other tests failed to reveal gamma-rays with superhigh energies exceeding 10^{14} eV. Today, it is clear that superhigh-energy gamma-photons, if any, cannot be detected using available experimental facilities which are at best suitable for recording EAS. The maximum photon energy documented to date is 2×10^{13} eV (Crab radiation) (see [41b], Vol. 2, p. 315). Detection of gamma-rays with energies higher than that is the principal objective of the aforementioned projects focussed on constructing large-surface installations [59, 65].

There is a large number of papers concerned with cosmic ray acceleration. Some of these studies were designed to elucidate acceleration patterns of electron and proton-nuclear components of shock waves generated during flares of supernovae [67]. Acceleration of superhigh-energy particles was considered in Ref. [58] which cites some other papers on the subject. In addition, more new data and ideas can be found in [41b] (Vol. 3 pp. 329 – 368). It is likewise worthy of note that Ref. [68] revealed correlation between directions of the observed EAS with the highest energies and directions toward the plane of Local Supercloster. Nevertheless, despite all these findings, the sources of superhigh-energy particles remain to be identified.

Antiprotons in cosmic rays were first discovered as late as 1979 [69]. Results of this study were updated in Ref. [70]. Specifically, it has been shown that the ratio of the antiproton flux $\bar{p}$ to the proton flux p in the energy range from 4 to 19 GeV equals 1.52×10^{-4}. This finding is in agreement with the estimates obtained on the assumption that antiprotons are generated in the Galaxy in collisions between cosmic rays and interstellar gas nuclei.

Reports on the detection of antinuclei (e.g., antihelium nuclei) are lacking from the literature (see, for instance, Ref. [41]). At the same time, Ref. [71] indicates that $\overline{\mathrm{He}}/\mathrm{He} < 8 \times 10^{-6}$ at the boundary of the atmosphere.

Of late, there has been a great deal of talk about a project to search for antinuclei using a large recording device aboard a space station. In connection with this, it seems appropriate to note that the probability of a positive result in such an experiment is negligible. Indeed, cross-sections for antinuclei generation by cosmic rays in the Galaxy are very small. Antinuclei in cosmic rays that reach us from other galaxies would be possible to detect only if there were galaxies composed of antimatter (it is precisely this possibility that the authors of the project appear to have relied upon when they designed the study). However, the existence of such antigalaxies is questionable since they have never been observed or predicted (antigalaxies might serve as sources of strong gamma-radiation upon mutual annihilation of matter and antimatter on their boundaries).

The above comments may look like having a critical slant. It is therefore opportune to emphasise once again the indisputably great progress in cosmic ray astrophysics and related scientific disciplines. There is little doubt that we shall witness more discoveries and achievements in the near future (suffice it to mention forthcoming results of observations on high-energy cosmic neutrinos which are soon expected to be available for discussion).

I would like to thank V S Ptuskin for his critical reading of the manuscript.

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