The origin of cosmic rays (past, present, future)[1]

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The first part of the article is a lecture prepared for the 15th International Conference on Cosmic Rays (Plovdiv, Bulgaria, August 1977). In addition to historical aspects a number of questions are discussed in the lecture concerning the present state of the problem of the origin of cosmic rays. Among them are the following: proof of the existence of a cosmic ray halo and a radio halo of our Galaxy and a discussion of the relation between the homogeneous galactic model and the halo model as applied to radioactive nuclei (specifically, to ^{10}Be nuclei). The Appendices present some information on the work of the 15th International Conference on Cosmic Rays and also a number of remarks complementing the lecture in the light of new data, etc.

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International conferences on cosmic rays have been regularly held already for three decades and they are naturally devoted mainly to recent results. Therefore, the subtitle of my lecture (past, present, future) looks somewhat strange and may even be pretentious. And yet some delving into history appears appropriate for a number of reasons. Firstly, the present report is scheduled for the first plenary meeting and, therefore, is intended for a rather general audience. Secondly, and this is even more essential, the history of cosmic ray research is not only interesting in itself, but can also provide a better insight into the development of this field at the present time and make certain predictions for the future. Attempting to touch upon a wide range of questions, including historical ones, in a single paper we have to forego, of course, a discussion of a number of important details and even of entire directions of research. However, quite extensive specific material concerning the origin of cosmic rays has been presented at the conference, and it is hoped, therefore, that this report of a somewhat different character is also relevant.

1. Cosmic rays were discovered by V. Hess in 1912. Although Hess had predecessors, it was he who after several balloon flights convincingly showed the following: the ionization rate (the number of ion pairs produced per unit time) in airtight vessels filled with air increases with height when moving away from the earth's surface (higher than one kilometer); thus in his most successful flight that took place on August 7, 1912, Hess reached a height of 5 km, where the ionization rate already showed an increase of several fold. These results were confirmed by W. Kohlhörster, who reached (in 1914) a height of 9 km, where the ionization rate is already by an order of magnitude higher than at the earth's surface (even taking radioactive background into account)[2]. After that there remained no doubt that some penetrating radiation was coming from above. However Hess's conclusion concerning the extraterrestrial (cosmic) origin of the observed radiation is more far-reaching. To prove it one had to exclude the possibility that the observed radiation was γ radiation from radioactive substances present in the upper layers of the atmosphere. Although Hess had already presented some evidence against such a possibility (independence of the ionization rate of the time of day, of weather, etc.), it was excluded with much difficulty only after several years of work carried out between 1922 and 1928 for the most part by the group of R. Millikan and by the group of L. V. Mysovskiĭ. It is worth noting that at these early stages (1922–1923) Millikan nearly "extinguished" cosmic rays on the basis of an erroneous conclusion concerning the coincidence of their absorption coefficient with that of the known γ-rays from radioactive elements. However, later both these groups as well as other authors established convincingly that absorption of cosmic rays is weaker than that of γ radiation from radioactive substances. All doubts about the existence of cosmic rays, i.e., of a penetrating radiation of extraterrestrial origin, disappeared in general only somewhere in 1927–1928. However, Hess was awarded the Nobel Prize in physics "for his discovery of cosmic radiation" only in 1936, and this apparently reflected the long-standing doubt if not concerning the discovery itself, then concerning its significance (according to the statute, Nobel Prizes are conferred "for the most recent achievements ... and for older work, only in cases in which its significance has not been recognized until recently").

2. Thus, it took 15 years merely to prove the extraterrestrial origin of cosmic rays. Then the centre of gravity in their study for a long time moved to the use of cosmic rays as a natural "source" of high-energy particles. It is well known that along this path a glorious page was added to the history of physics. It is in cosmic rays that discoveries were made of positrons

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[1] Invited paper prepared for the 15th International Conference on Cosmic Rays (Plovdiv, Bulgaria, August 13-26, 1977). Only very insignificant alterations have been made in the text of that lecture as presently published in Usp. Fiz. Nauk. This version, however, contains appendices devoted to some recent data and results, particularly to those presented at the Conference.

[2] For more details see paper [1] submitted to the Conference (see also the original literature cited there).

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(1932), μ-mesons (1937), $\pi^{\pm}$-mesons (1947), K^0- and $K^{\pm}$-mesons (1947–48) and Λ-, $\Sigma^{\pm}$- and Θ^{-}-hyperons. Construction of high energy particle accelerators and increasing difficulties in cosmic ray studies with increasing energy considerably reduced the relative importance of investigations in high-energy physics with the aid of cosmic rays. But above the limit of energy reached with accelerators (for protons this energy now is $E \approx 5\times10^{11}$ eV)3)/cosmic rays are the only source of superhigh energy particles (energy up to 10^{20} eV). Therefore, in spite of all the difficulties due to the decrease of cosmic-ray intensity with increasing energy and due to the possibility in a number of cases of studying only secondary phenomena (extensive showers, etc.), cosmic rays are still being used in high-energy physics. But this is not my topic, and I only presume to disagree with the position of critics and sceptics who have been already for 20 years "burying" cosmic rays as a source of important physical information. Of course, once there is an accelerator for a given energy range, it is the source that must be used. There is no doubt also that as energy increases it becomes more and more difficult to use cosmic rays. But technical possibilities have also increased (suffice it to mention satellites, particularly very heavy ones, huge scintillators and spark chambers, etc.). As for a guarantee of success, there also was none before the discovery in cosmic rays of positrons, mesons and hyperons. Thus, further development of high-energy physics in cosmic rays seems fully justified, and it would be blindness to deny the existence here of attractive possibilities.

3. As far as the astrophysical aspect of cosmic-ray research is concerned, it had remained in the shadows up to 1950–1953. Of course, the question of the origin of cosmic rays had already been posed, but even the very nature of primary cosmic rays had long been unclear. At first they were considered to be hard γ-rays. After the discovery of a latitude geomagnetic effect (1927–1936) it became clear that primary cosmic rays incident on the boundary of the atmosphere are charged particles, preference at first being given to electrons. The data on the East-West asymmetry (1933 and later) tipped the scales in favor of protons. The role of protons as the main component of primary cosmic rays was confirmed by direct measurements with high-altitude balloons. Then (1948) primary cosmic rays were found to contain also nuclei of a number of elements. The intensity of the primary electron component was not successfully measured at that period, although an indication of an upper limit (of the order of 1% of the total cosmic-ray flux) already seemed significant.

Thus the composition of primary cosmic rays had already been roughly established by 1950. A number of papers had also appeared by that time anticipating the potential importance of cosmic rays for astrophysics. For example, as far back at 1934 W. Baade and F. Zwicky associated[2] supernova explosions with neutron star formation and cosmic ray generation. In 1949 Fermi[3] treated cosmic rays as a gas of relativistic particles moving in interstellar magnetic fields and thus anticipated the further study of the problem to a considerable extent4). Nevertheless the role of cosmic rays in astrophysics as a whole was appreciated neither by astronomers nor by physicists until the fifties. In general, this is easy to understand. If the action of the earth's magnetic field is excluded, cosmic rays arrive at the boundaries of the earth's atmosphere very isotropically—with the same intensity from all directions (we do not take solar cosmic rays into consideration). Therefore even a detailed knowledge of the composition and energy spectrum of cosmic rays near the earth is analogous to the information about the spectrum of all the stars taken together. It is easy to imagine in what an imperfect state astronomy would be under such conditions, i.e., if we could not see individual stars.

4. But in any case it seems to me that cosmic ray astrophysics or, as it has lately been called, high energy astrophysics5) was born only after the connection between cosmic rays and cosmic radio-emission was established. As is known, cosmic radio-emission was discovered by K. Jansky in 1932, but a thorough study of it began only in 1945–46 (the first, apart from the sun, discrete source of cosmic radio-emission, radiogalaxy Cyg A, was discovered in 1946). At first attempts were made to associate nonthermal cosmic radio-emission with processes that lead to sporadic solar radio-emission but proceed in atmospheres of particularly active stars (radio-star hypothesis). However in 1950 another hypothesis appeared—that of synchrotron radiation, and, specifically, attention was paid to the effectiveness of the synchrotron mechanism of generation of cosmic radio-emission.[5–7] It took, however, several years to remove practically all doubts that the main part of nonthermal cosmic radio-emission is specifically of synchrotron origin, i.e., it is generated by relativistic electrons that are moving in cosmic magnetic fields. The history of the corresponding discussions is rather curious and even dramatic, but I shall not dwell on this topic here since as a participant in these discussions I may be not objective enough. And in general I would not want to have questions of history distract us unnecessarily from the essence of our subject.

So, it became clear only 20–25 years ago (or 40–45 years after the discovery of cosmic rays) what an outstanding role cosmic rays play in the Universe. In particular, it became clear that cosmic rays are a universal phenomenon: they are present in the intersteller space of our Galaxy, in supernova remnants and in other

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3) In the center-of-mass reference system the energy of each of two colliding protons is $E_c = (\frac{1}{2}Mc^2E)^{1/2}$ (here M is the proton mass and it is assumed that $E \gg Mc^2$). Hence, $E = 2E_c^2/Mc^2$ and, therefore, the use of colliding beams of protons with energy $E_c = 5\times10^{11}$ eV *corresponds to the cosmic-ray* study of protons of energy $E \sim 5\times10^{14}$ eV. However, it will be possible to use such colliding beams only in the next decade.

4) References 2, 3 as well as a number of other papers devoted to the origin of cosmic rays are reprinted in the collection of Ref. 4.

5) Since it is only charged particles that are now called cosmic rays, high energy astrophysics, which comprises also X-ray and gamma-ray-astronomy, is broader than cosmic ray astrophysics, at least in a literal use of the latter term.

galaxies, being particularly numerous in radio-galaxies. This is essential firstly in connection with the fact that radio waves (and we now can also say X- and γ-rays) generated by cosmic rays are a source of very valuable astronomical information. Secondly, the cosmic ray energy density w_{cr} and pressure $p_{\mathrm{cr}} = w_{\mathrm{cr}}/3$ (we have in mind here a gas of isotropic relativistic particles) turned out to be rather significant, important or sometimes even dominant from the point of view of the energetics and dynamics of supernova remnants, galactic haloes, radiating clouds in radio-galaxies, etc. (for the history of the question see Refs. 8–10 and the literature cited therein).

We should, however, introduce an essential caveat. Knowing the intensity and the spectrum of synchrotron radiation one can find the intensity and the energy density $w_{\mathrm{cr},e}$ of radiating relativistic electrons (i.e., in this case of the electron or more precisely, of the electron-positron component of cosmic rays) only if one knows the intensity and orientation of the magnetic field **H** in the radiating region. Further, in order to pass from the electron to the main proton-nuclear component of cosmic rays (or, specifically, to find w_{cr}, knowing $w_{\mathrm{cr},e}$) we must establish the ratio of the intensities of the two components. Near the earth this ratio is of the order of one per cent ($w_{\mathrm{cr}} = \varkappa_r w_{\mathrm{cr},e} \sim 10^2 w_{\mathrm{cr},e} \sim 10^{-12}$ erg/cm^3). Regarding the intensity of the field **H**, using the assumption of equipartition of energy among the "degrees of freedom", as well as a number of other indirect arguments, the field is usually considered to be quasi-isotropic with $H^2/8\pi = \varkappa_H w_{\mathrm{cr}} \sim w_{\mathrm{cr}}$, i.e., it is assumed that $\varkappa_H \sim 1$. Thus, if one uses only radiodata, one must introduce two coefficients $\varkappa_r = w_{\mathrm{cr}}/w_{\mathrm{cr},e}$ and $\varkappa_H = H^2/8\pi\omega_{\mathrm{cr}}$. The assumption that $\varkappa_r \sim 10^2$ and $\varkappa_H \sim 1$ is, of course, a particular choice, but it is quite reasonable for objects of quasi-stationary type, like our Galaxy (the point is that the life-time of cosmic rays in the Galaxy as a whole is rather long, they undergo mixing and, finally, their intensity changes slowly, if at all). Therefore, estimates of the energy of cosmic rays in galaxies and radio-galaxies that in the latter case attain values of $W_{\mathrm{cr}} \sim 10^{60}$–$10^{61}$ erg $\sim (10^6$–$10^7)\ M_\odot c^2$ seem well-founded.

Clarification, even in general terms, of the astronomical role played by cosmic rays and their connection with cosmic radio-emission is, of course, one of the greatest achievements of astronomy in our century, and now high-energy astrophysics is one of the most important fields of astrophysics. One of the directions in this field is the problem of the origin of cosmic rays observed near the earth. I would like to emphasize that we are here dealing with just one of the directions of research which is by no means more important compared with, say, the problems of generation and propagation of cosmic rays in radiogalaxies and quasars.

At the same time it is obvious that just the problem of the origin of cosmic rays observed near the earth is closely connected with the physics of cosmic rays and with the topics of the present conference.

5. To solve the problem of the origin of primary cosmic rays observed near the earth[6] is to indicate the sources both of the proton-nuclear and of the electron-positron components of cosmic rays. The energy spectrum, the composition and the high degree of isotropy of all the components must also be explained. Acceleration of cosmic rays within their sources is a separate topic. Some picture or model must practically be taken as the basis of consideration (one often also hears of theories of the origin of cosmic rays, but the use of such terminology is hardly justified).

Various models of the origin of cosmic rays have been suggested: solar, galactic and metagalactic, depending on the location of the main cosmic ray sources. We cannot dwell upon all these models that have been proposed in various versions (cf., Refs. 4, 10). I shall venture to go over directly to the model which seemed most reasonable and probable as far back as 1953 (cf., review 8). In this model cosmic rays are formed in the Galaxy and are "trapped" in it in a quasistationary manner. The principal sources are supernovae. The trapping region is a quasispherical halo (radius $R \sim 10$–15 kparsec). The characteristic lifetime (escape time for protons) is $T_{\mathrm{cr}} \sim (1-3)\times 10^8$ years. Since the volume of the system (of the trapping region) is $V \sim 10^{68}$ cm^3 and the cosmic-ray energy density is $w_{\mathrm{cr}} \sim 10^{-12}$ erg/cm^3 (data near the earth), the total cosmic-ray energy in the Galaxy is $W_{\mathrm{cr}} \sim w_{\mathrm{cr}} V \sim 10^{56}$ erg, and the power of the sources is $U_{\mathrm{cr}} \sim W_{\mathrm{cr}}/T_{\mathrm{cr}} \sim (1-3)\times 10^{40}$ erg/sec. For the electron component $W_{\mathrm{cr},e} \sim 10^{54}$ erg and taking energy losses into account $U_{\mathrm{cr},e} \sim 3\times 10^{38}$–$3\times 10^{39}$ erg/sec. All these estimates are, of course, rough and are given for purposes of orientation.

In my opinion at the present time the above mentioned model and its parameters are still the most probable ones. At the same time, now, almost twenty-five years after its appearance, the "Galactic model with halo" is still not proved and, more than that, it encounters objections. And this, like the previous stages in the history of cosmic ray research, is quite instructive: for a whole set of problems and fields in science 20–30 years turn out to be not such a long period. And yet rapid progress in some other fields, an increase in the number of physicists and astronomers and, what is also essential, a commensurability with the duration of the active phase of a human lifetime make people, particularly young people, think of events of twenty-five years' remoteness almost as of prehistoric ones.

Thus, the problem of the origin of cosmic rays cannot be regarded as solved in the sense that a generally accepted model is still lacking that would describe gen-

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[6] Hereafter we shall deal only with these cosmic rays, and more precisely with their main component which originates outside the solar system (we shall not keep repeating this remark in what follows). Naturally, solar cosmic rays and various modulation effects connected with the propagation of cosmic rays in interplanetary space, and also in the earth's magnetosphere and atmosphere are of great interest from many points of view (see Ref. 35 and the literature cited there) but we cannot touch also upon this range of questions here.

eration, propagation and "trapping" of the main part of cosmic rays observed near the earth.

What has been said does not mean, of course, that little has been achieved in cosmic ray astrophysics in the last twenty-five years. Progress in this field is obvious. We shall make only a few remarks about it (cf., reviews 11–17). Thus, in 1961 primary cosmic rays were found to include electrons and their spectrum began to be determined. In 1965 relict cosmic radioemission (with a temperature of 2.7 °K) was discovered. The energy density of this radiation in intergalactic space is so high ($w_{\mathrm{ph}} \approx 4\times10^{-13}$ erg/cm^3) that relativistic electrons (with an energy $E \gtrsim 10^{10}$ eV) cannot reach our Galaxy even from the nearest radio-galaxies due to losses by the inverse Compton effect. This proves the galactic origin at least of the main part of the electron component observed near the earth. Great success has been achieved in the study of the chemical composition of cosmic rays. Finally, γ-ray astronomy was born (1968–1972), and its development will provide valuable information. We would particularly emphasize the possibility (essentially the only one known) of determining the intensity of the main proton-nuclear cosmic ray component far from the earth by a gamma-astronomical method. It implies that collisions of the proton-nuclear component with nuclei of the interstellar (and, in general, cosmic, e.g., intergalactic) medium produce unstable particles, first of all π^0-mesons which decay emitting γ-rays. As a result, if the density of the medium is known, a measurement of the intensity of the appropriate part of the cosmic γ-rays makes it possible to determine the intensity and, therefore, the energy density w_{cr} of the cosmic-ray proton-nuclear component (for more details cf., Refs. 11–17). By the same token in order to find w_{cr} one no longer needs to introduce the coefficients $\varkappa_r$ and $\varkappa_H$.

All these achievements have led also to progress in solving the problem of cosmic ray origin. But, as follows from what has been said, these achievements are yet insufficient for an unambiguous and totally convincing solution of the problem.

We now turn to a discussion of the present state of the problem of the origin of cosmic rays and concentrate attention on the basic question of the choice of a realistic model.

6. An alternative to galactic models of cosmic-ray origin are metagalactic models.7) In these models the main part of the cosmic-ray proton-nuclear component is thought of as entering the Galaxy from intergalactic space. Galactic and metagalactic models have been repeatedly compared (cf., Refs. 10, 11, 14 and the literature cited there). The latest rather detailed paper known to us that contains arguments in favor of a metagalactic model was written by G. Burbidge.[18] Counterarguments are briefly listed in Ref. 19 and reduce to energy estimates, to a comparison between proton-nuclear and electron components, to the employment of certain extragalactic and gamma-astronomical data and also to a possible isolation of metagalactic cosmic rays from regions inside the Galaxy.[20] In my opinion all these considerations taken together lead us to think that metagalactic models are quite improbable. This refers particularly to the universal (quasihomogeneous) metagalactic model in which cosmic rays fill the whole Metagalaxy more or less uniformly (here we do not touch upon the dependence on the red shift parameter z). By the way, even in Ref. 18 this model has been abandoned (if one leaves out of consideration protons of energy $E \geqslant 10^{16}$ eV). Of the "local" metagalactic models the most attention is now attracted to the model of a local supercluster of galaxies (supercluster in Virgo) in which the main part of the proton-nuclear component is formed in the supercluster. In such a case some of the above mentioned objections are not as convincing as in the case of a universal model. Thus, we may say that the "local" metagalactic model has not yet been convincingly disproved.

How should this be accomplished? The main difference between matagalactic and galactic models is that in the latter the cosmic-ray energy density in metagalactic space is $w_{\mathrm{cr},Mg} \ll w_{\mathrm{cr,G}} \equiv w_{\mathrm{cr}} \sim 10^{-12}$ erg/cm^3 (whereas in metagalactic models $w_{\mathrm{cr},Mg} \approx w_{\mathrm{cr}} \sim 10^{-12}$ erg/cm^3, and cosmic rays are more or less uniformly distributed for example, throughout a local supercluster including the Galaxy). Thus, to disprove metagalactic models it is sufficient to show that outside the Galaxy, but close to it $w_{\mathrm{cr},Mg} \ll w_{\mathrm{cr}}$. If one speaks of direct observations, it is only the gamma-astronomical method that suits this purpose. Specifically, the most reliable possibility is measurement of the gamma-ray flux from the Magellanic Clouds.[21] The amount of gas in these Clouds is known, and, therefore, if in them we also have $w_{\mathrm{cr},MC} \approx w_{\mathrm{cr},Mg} \approx w_{\mathrm{cr}}$, they must emit γ-rays, whose flux on earth is $F_\gamma(E_\gamma > 100\ \mathrm{MeV}) \approx 3\times10^{-7}$ photons/cm^{2}sec (two thirds of this flux relate to the Large Magellanic Cloud and one third must be produced in the Small Cloud). If the measured flux will prove to be much smaller than the above mentioned one, it seems to me that metagalactic models will be disproved sufficiently rigorously. But apparently one will have to wait for such measurements for several years. Therefore, it is natural to make use of measurements of intensity of galactic γ-emission both from the region of the anticenter[22] and also from other directions.[17,23] In metagalactic models the density w_{cr} must not appreciably decrease with distance from the galactic center or the galactic plane. But some gradients are still possible, one must also know the lower limit of gas density in the corresponding regions. Hence, the available data,[22,17,23] although testifying against metagalactic models can hardly be considered as providing definite proof. At the same time it is clear that the creation and development of the gamma-astronomical method, which in general must be regarded as the main achievement in cosmic ray astrophysics in recent years, at last opens up a possibility of convincingly solving the problem under discussion. Although some uncertainty remains in this case, we shall in what follows proceed from the

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7) Here we do not touch upon cosmic rays of superhigh energy $E \gtrsim 10^{17}$ eV (production of the main part of cosmic rays in our Galaxy by no means excludes the possibility of particles of superhigh energy being of metagalactic origin).

assumption that cosmic rays originate in the Galaxy (we emphasize once again that we do not touch upon the superhigh energy region).

7. To choose the galactic model of the origin of cosmic rays is still not enough to make such a model specific. Indeed, galactic models may be quite different. The difference between the disk and the halo models is of particular importance. As has already been mentioned, in models with a large halo cosmic rays fill a quasispherical (or a somewhat more compressed ellipsoidal) volume with the following characteristic dimensions R and life-time (escape-time) $T_{\mathrm{cr},h}$:

$$R \sim (3-5)\cdot 10^{22}\,\mathrm{cm}, \quad T_{\mathrm{cr},h} \sim \frac{R^2}{2D} \sim (1-3)\cdot 10^{8}\,\mathrm{years}\,,$$

which correspond to an effective diffusion coefficient D and a mean free path l of the order of:

$$D \sim \frac{lv}{3} \sim 10^{29}\,\mathrm{cm}^2\ \mathrm{sec}^{-1}, \quad l \sim 10^{19}\,\mathrm{cm}\,.$$

In the lower part of the halo and particularly in the disc the values of D should naturally be considered to be somewhat lower. In this case the sources are located in the galactic disc of half-thickness $h_s \sim (3-5)\times 10^{20}$ cm and are for the most part supernovae (including pulsars) or are located in the galactic center; in the latter case we speak of cosmic-ray generation accompanying an explosion of the galactic nucleus (model with a halo and a source at the center). It is well known that the galactic gas is concentrated in a disc of just the indicated half-thickness $h_g \sim h_s \sim 100-150$ parsec $\sim (3-5)\times 10^{20}$ cm with an average density of $\bar{n} \sim 1\ \mathrm{cm}^{-3}$.

Physical considerations connected with the dynamics of a system that contains cosmic rays, gas and magnetic fields testify in favor of halo models. Emerging from such a "system" (and specifically, from the galactic disc) cosmic rays must drag the field with them and, probably, introduce turbulence. As a result the source region must be surrounded by a region in which cosmic ray intensity is still high and transition to metagalactic space takes place only at some rather large distance from the source region. Something of the kind is actually observed, since at any rate galactic radio-emission occupies the region of a radiodisc of half-thickness $h_d \gtrsim (1-3)\times 10^{21}$ cm, which clearly exceeds the assumed disc half-thickness of the source disc $h_s \sim 3\times 10^{20}$ cm. Moreover, we know of no grounds to prevent the further "swelling" of the cosmic-ray trapping region and a transition to a halo of half-thickness $h_h \sim R \sim (1-5)\times 10^{22}$ cm is more natural.

It is logically possible that cosmic rays (the proton-nuclear component) and the electron component have different trapping regions. It is, however, more probable and natural that the existence of a "cosmic-ray halo" is responsible for the presence of an analogous halo for relativistic electrons (however, due to additional losses, for the most part synchroton and Compton losses, an effective halo dimension for electrons of sufficiently high energy may well turn out to be much smaller than the cosmic ray halo dimension). But the electron halo must be observed as a radio-halo. Thus, the discovery of a radio-halo of the Galaxy would practically prove the existence also of a cosmic-ray halo, i.e., in general it would prove the validity of galactic models with halo. Unfortunately, though the question of a galactic radio-halo has been discussed for 25 years, it has not yet been finally settled. At first there was no doubt of the existence of a large radio-halo,[8-10] but later, on the contrary, the presence of a radio-halo was sharply denied. In general, this question has assumed, in a strange way, an unpleasant character. The latter circumstance is reflected in one of the recent papers by J. Baldwin who writes[24]: "In the discussion so far I have avoided the use of the phrase "radio-halo." It arouses antagonism in otherwise placid astronomers and many have sought to deny its existence." One might conjecture that the irritation in this question may arise as a reflection of the feeling of helplessness arising as a result of attempts to answer what seems to be a simple question. The difficulty here is in essence, that we are inside the halo and do not know distances to different regions of enhanced radio-brightness that are located in the radio-disc. But still the problem can be solved on the basis of observations of the radio-emission intensity as a function of direction (i.e., of galactic coordinates) for a whole set of frequencies. A correct treatment of the material is very important here. If calculations are based on some spectrum of the electron component with a density $N_e(\mathbf{r}, E_e)$, then the function N_e must be obtained from an equation, e.g., a diffusion equation, with losses taken into account. Further, the radio-emission intensity must be calculated by an appropriate integration along the line of sight as well as by integration over electron energies E_e. In this manner it has been concluded recently[25] (cf., also Refs. 15, 26) that the best agreement with observations is obtained when the Galaxy has a radio-halo of characteristic dimension R not less than 5–12 kparsec and with a high emissivity, which is smaller but of the same order as the disc emissivity. In Ref. 27 another method was employed to extract a radio-halo and it was concluded that although a halo does exist, its emissivity is 30 times lower than for the radio-disc. However, in Ref. 26 by the method used in Ref. 27 but taking the behavior of the radiating electron spectrum into account in a more detailed and accurate manner, the conclusion of Ref. 25 was confirmed: the radio-halo of the Galaxy is not only large but also its luminosity is high (by an order of magnitude higher than in Ref. 27).

The long history of the attempts to answer the question concerning the existence of a radio-halo makes us take particular care. But one may state that the recent results[25,26] testify definitely in favor of a powerful radio-halo of the Galaxy. The data presented in Ref. 24 give the same evidence (in the radio-disc model the disc thickness should evidently by doubled and reach 1.5 kparsec instead of the previous 0.75 kparsec; cf., also Ref. 36). And finally, some quite convincing data were obtained on the existence of a powerful radio-halo in certain spiral galaxies observed "edge-on." As far as the radio-galaxy NGC 4631 is concerned, the corresponding data are presented in Ref. 28a. Some information about a radio-halo of the galaxy NGC 891 is con-

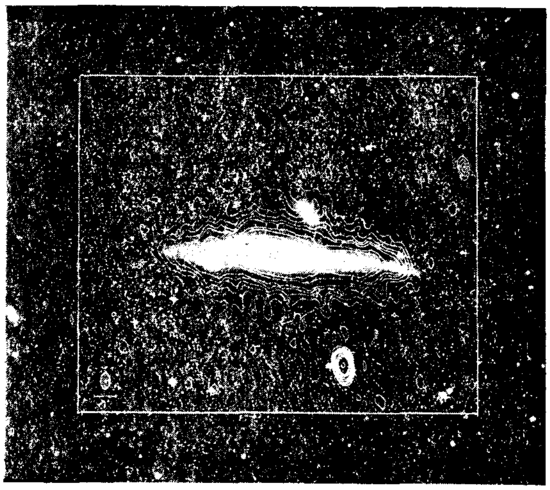

FIG. 1. Radio isophotes (lines of equal brightness) of galaxy NGC 4631 in the continuum for wavelength $\lambda = 21.2$ cm (frequency $\nu = 1412$ MHz). The radio-isophotes are superimposed on an optical image of the galaxy. In the lower left-hand corner of the figure is shown the effective angular width of the polar diagram of the radiotelescope.

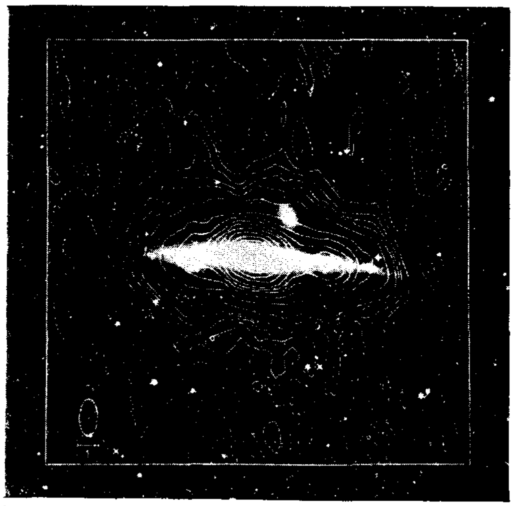

FIG. 2. Radio isophotes of galaxy NGC 4631 for waves with $\lambda = 49.2$ cm (frequency $\nu = c/\lambda = 610$ MHz). From a comparison of Figs. 1 and 2 it is clear that at longer wavelengths the halo is more pronounced and, specifically, is larger in dimensions.

tained in Ref. 24, then was reported by R. Sancisi at the IAU Assembly in Grenoble (August 1976) and, finally, was presented in detail in Ref. 28b. The results obtained for these galaxies are illustrated by Figs. 1–4 (the necessary explanations are contained in the figure captions).[8] We emphasize that for both galaxies NGC 4631 and NGC 891 an increase of the spectral index α(intensity $I_r(\nu) = C\nu^{-\alpha}$) is clearly seen with increasing distance from the disc (for NGC 4631 in the interval 610–1412 MHz $\alpha = 0.6$ in the disc and $\alpha = 1.0$ when receding from the disc; for NGC 891 the previous statement is clear from Fig. 4). Such behavior of the index α in a qualitative respect is just what should be expected in the case of diffusion (with losses) of relativistic electrons from the disc to the halo boundaries. Of course the presence of large radio-haloes in other spiral galaxies does not give direct evidence of a radio-halo of our Galaxy, but it surely supports the halo model (this is particularly valid for NGC 891 whose type and parameters are rather close to those of our Galaxy).

Thus, although with a delay of two decades, the problem of the galactic radio-halo seems to be approaching its solution. One cannot, however, refrain from making a preliminary conclusion in favor of a powerful galactic radio-halo and, therefore, of a powerful cosmic-ray halo of our Galaxy.

8. Long-standing doubts and even a denial of the presence of a halo gave rise to interest in the disc models. Moreover, some arguments appeared in favor of the estimate of the age of cosmic-rays $T_{cr} \sim T_{cr,d} \sim (1-3)\times 10^6$ years based on the determination of the amount of the radioactive isotope ^{10}Be in cosmic rays near the earth. This conclusion is, however, based on a misunderstanding as was already shown at the last conference[29] and was presented in detail in Ref. 15 and in report 30 submitted to the present conference. The point is that in the case of stable isotopes the results of the analysis of the cosmic-ray chemical composition are not very sensitive to the choice of the model and the basic parameter is the interstellar gas thickness $\bar{x}$ traversed by the nuclei. A weak dependence of the thickness x on the model parameters allows us to make wide use of a homogeneous (or the so-called leaky box) model in the analysis of the chemical composition of cosmic-rays. In this model the density N_i of stable secondary nuclei (i.e., nuclei absent in the sources) is determined by the equation (for details cf., Ref. 15)

FIG. 3. Radio isophotes of galaxy NGC 891 for wavelength $\lambda = 21.2$ cm. Even at such a comparatively short wavelength the halo is clearly pronounced. For wavelength $\lambda = 49.2$ cm the halo is still larger but is quite noticeable even at a wavelength of $\lambda = 6$ cm, as can be seen from Fig. 4.

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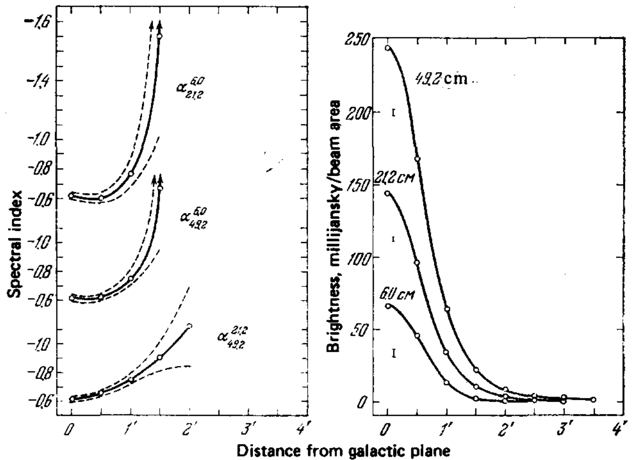
[8] The author is grateful to R. Sancisi for providing Figs. 1–4 contained in the papers of Ref. 28.



a) b)

FIG. 4. Galaxy NGC 891. Diagram a) shows the spectral index α (here, for example, $\alpha^{21.2}_{49.2}$ is the spectral index in the wavelength interval from 21.2 to 49.2 cm). The dashed line indicates values that are still possible with the available accuracy. Diagram b) shows the dependence of radio brightness (intensity) for wavelengths of 49.2, 21.2 and 6.0 cm on the distance from the galactic plane in the direction perpendicular to this plane. The brightness is plotted in mJy/beam area (recall that the flux unit or Jansky corresponds to the flux or, more precisely, to the flux spectral density, equal to 10^{-26} $w/m^2\text{Hz} = 10^{-23}$ erg/cm^2 sec Hz; the beam area, i.e. the polar diagram of the radio telescope, is to be interpreted as the solid angle corresponding to this diagram). If the distance to galaxy NGC 891 is assumed to be equal to 14 Mparsec, then 1′ along the abscissa corresponds approximately to 4 kparsec. Thus the size of the halo clearly exceeds 8 kparsec, and if we have in mind the size corresponding to half-brightness, then this dimension is not less than 4 kparsec.

$$N_i\left(\frac{1}{x}+\sigma_i\right)=\sum_j \sigma_{ij}N_j,\quad x=\bar{n}cT_{\text{cr}}^{(\text{hom})},$$

where σ_i is the effective cross section for the transformation ("disappearance") of a nucleus of i type and σ_{ij} are cross sections corresponding to the transformation of heavier nuclei of j type into nuclei of i type in collisions in the interstellar gas (all the nuclei are considered to be relativistic, i.e., moving with a velocity close to the velocity of light c); if the thickness x is measured in g $\cdot$ cm^{-2}, then for the interstellar gas (the mean density $\bar{\rho}\approx 2\times 10^{-24}$ $\bar{n}$) we have

$$x\approx 2\cdot 10^{-24}\bar{n}cT_{\text{cr}}^{(\text{hom})}.$$

From observations it follows that $x\sim 6.5$ g $\cdot$ cm^{-2} (for pure hydrogen this corresponds to the value $x\approx 5$ g $\cdot$ cm^{-2}). From this we obtain $T_{\text{cr}}^{(\text{hom})}\approx 3\times 10^6/\bar{n}$ years. If the cosmic-ray "trapping" region is a gas disc, where $\bar{n}\sim 1$ cm^{-2}, then $T_{\text{cr}}^{(\text{hom})}\sim T_{\text{cr},d}\sim 3\times 10^6$ years. It is clear, however, that the density $\bar{n}$ is not known in advance. If cosmic rays are trapped in a halo (but also passing through a disc) it is reasonable to use the value $\bar{n}\sim 10^{-2}$ cm^{-3} and then already $T_{\text{cr}}^{(\text{hom})}\sim T_{\text{cr},h}\sim 3\times 10^8$ years.

To establish the lifetime of cosmic rays one may use measurements of the amount of radioactive isotopes. If we here take the homogeneous model, then in the above equation for N_i we must substitute $(1/x)+(1/\bar{n}c\tau_i)$ for $1/x$, where τ_i is the mean lifetime of the isotope N_i. Knowing N_i and the value of x (from stable isotope measurements), we can then find the time $T_{\text{cr}}^{(\text{hom})}$, and thus the mean density $\bar{n}$.

For ^{10}Be nuclei decaying into ^{10}Be + e^- with the mean lifetime $\tau_i\equiv\tau=2.2\times 10^6$ E/Mc^2 years estimates of $T_{\text{cr}}^{(\text{hom})}\sim 3\times 10^6$ years were obtained. This result has been taken as an argument in favor of the disc models. According to the latest data $T_{\text{cr}}^{(\text{hom})}\approx 2\times 10^7$ years[31] and $T_{\text{cr}}^{(\text{hom})}=5^{+6}_{-3}\times 10^6$ years,[32] which is also noticeably smaller than $T_{\text{cr},h}\sim(1-3)\times 10^8$ years characteristic of the galactic model with a halo. But in this model the time $T_{\text{cr},h}\sim R^2/2D$ has the meaning of the time of diffusion from the disc (sources) to the halo boundaries. For stable nuclei occupying the whole halo the time $T_{\text{cr},h}\approx T_{\text{cr}}^{(\text{hom})}$ whereas for radioactive nuclei this is, generally speaking, no longer true. In fact, radioactive nuclei with the lifetime τ occupy practically the whole halo only if $\tau > T_{\text{cr},h}$. If $\tau < h_s^2/2D_s\sim T_{\text{cr},s}$—the time of escape from the source region (disc), radioactive nuclei will not enter the halo at all. For nonrelativistic ^{10}Be nuclei the time $\tau=2.2\times 10^6$ years and the time $T_{\text{cr},s}$ $\sim h_s^2/2D_s\sim 2\times 10^5$ years (for $h_s\sim 100$ parsec $\sim 3\times 10^{20}$ cm and $D_s\sim 10^{28}$ cm^{2}sec^{-1}), i.e., the inequalities

$$T_{\text{cr},s}\ll\tau\ll T_{\text{cr},h}\sim(1-3)\cdot 10^8\text{ years.}$$

hold. In this case[15,29,30] $T_{\text{cr}}^{(\text{hom})}\sim(R^2\tau/2D)^{1/2}\sim(T_{\text{cr},h}\tau)^{1/2}$ or $T_{\text{cr},h}\sim(T_{\text{cr}}^{(\text{hom})})^2/\tau$. From this with $T_{\text{cr}}^{(\text{hom})}\sim 2\times 10^7$ years (for nonrelativistic ^{10}Be nuclei) the time $T_{\text{cr},h}$ $\sim 2\times 10^8$ years. A reasonable complication of the model (introduction of different diffusion coefficients in the disc and the halo, and others) makes the relation between the conventional age $T_{\text{cr}}^{(\text{hom})}$ and the escape time $T_{\text{cr},h}$ depend already on a number of parameters. Therefore even the time $T_{\text{cr}}^{(\text{hom})}\sim 3\times 10^6$ years is quite compatible with the time $T_{\text{cr},h}\sim(1-3)\times 10^8$ years (cf., Ref. 30). Thus, the available data on the amount of ^{10}Be nuclei in cosmic rays do not in any sense contradict the halo model.

Obtaining more precise data on nonrelativistic ^{10}Be nuclei, transition to relativistic ones (for them the time τ is by a factor E/Mc^2 larger) as well as to other radioactive nuclei will allow us, at least in principle, to estimate the parameters of the models utilized (dimensions, diffusion coefficients in various regions, etc.). One must also have, of course, sufficiently exact data for stable nuclei.

The chemical composition of cosmic rays has already been studied for 30 years. And the fact that there are still many uncertainties in this field (specifically, the accuracy of measurements and calculations is insufficiently high) is due both to the complicated nature of the problem and to the absence of sufficiently accurate data on fragmentation cross sections for a large number of nuclear reactions. On the other hand, there is absolutely no doubt about progress, and, for example, only in recent years data on the change of the chemical composition with energy were obtained as well as some information on the amount of ^{10}Be, of very heavy nuclei, etc. (cf., Refs. 11–15). We may hope that in the near future data on the chemical and isotope composition of cosmic rays will become so extensive and accurate that it will be possible to complicate the available models and to choose between them.

It is, however, very difficult to free oneself from the assumption that the solar system is in about the same position with respect to the chemical composition of cosmic rays as the other regions in the disc. At the same time there is no guarantee that the chemical composition of cosmic rays near the earth is not to a large extent determined by some local source or, in general, that cosmic rays in the Galaxy are not too well mixed (such a possibility is essential also for the discussion of cosmic-ray anisotropy). But this is already another problem. Here we wish particularly to emphasize the fact that the available data on the chemical composition of cosmic rays do not, in any case, contradict galactic models with haloes.

As for the disc model with $T_{cr,d} \sim 3 \times 10^6$ years and cosmic-ray trapping in a gas disc with $h_s \sim (3-5) \times 10^{20}$ cm, it directly contradicts the radio-data. Indeed, while the question of radio-halo dimensions may be argued, it is generally accepted that the dimension of the radio-emitting region in the Galaxy is much thicker than the gas disc. Thus, if one introduces a radio-disc, then, as has already been mentioned, its half-thickness is $h_d \sim 3 \times 10^{21}$ cm. There is no doubt that cosmic rays (protons and nuclei) occupy an even greater region, and this implies that the mean gas density in the trapping region is $n \lesssim 0.1$. From this it follows that $T_{cr}^{(hom)} \gtrsim (1-3) \times 10^7$ years. Thus, if one undertakes to discuss a "disc model," only a disc with $h_d \gtrsim 3 \times 10^{21}$ cm may be considered, whereas for a quasispherical halo the characteristic *dimension in the direction perpendicular to the* galactic plane is $h_h \sim R \sim (3-5) \times 10^{22}$ cm.

Here I permit myself to remind the reader that at one of the conferences (it seems to me, at the International Conference on Cosmic Rays in Moscow in 1959) I suggested treating the equality $1 = 10$ as one of the fundamental laws of cosmic-ray astrophysics. And indeed, this "law" must not be forgotten when dealing with some order of magnitude estimates with the use of a number of simplifying assumptions so often encountered in astrophysics. In particular, when introducing the concept of a radio-disc, its emissivity, for example, is considered to be constant in a region of thickness $2h_d$. An assumption of a constant emissivity or of a constant density of radiating electrons, etc., is also used sometimes in radiohalo models. In reality, the density of cosmic rays, and especially of their electron component (at a given electron energy), decreases somewhat (with distance from the galactic plane); the same may evidently be said about the magnetic field strength. Under such conditions, unless a more exact definition of the concepts is given and a comparison of quantitative data is carried out, an argument as to whether there exists a sufficiently thick radio-halo remains an argument about words. A real comparison is, in particular, the one between the lifetime of cosmic rays in our Galaxy $T_{cr,h} \sim (1-3) \times 10^8$ years (a halo or a thick disc) and the time $T_{cr,d} \sim (1-3) \times 10^6$ years (a gas disc). As has been said, a model with such a thin disc contradicts radio-data, to say nothing of physical considerations. It is more difficult to disprove an intermediate disc model with $h_d \sim 3 \times 10^{21}$ cm and $T_{cr} \sim (1-3) \times 10^7$ years. However, even if one disregards the results of calculations of Refs. 25, 26, that testify in favor of a quasi-spherical halo, an increase in the dimensions and the lifetime of a "disc" (as compared with the values of $h_d \sim 3 \times 10^{21}$ cm and $T_{cr} \sim (1-3) \times 10^7$ years) seems natural if one takes into account a rather probable falling off of cosmic-ray intensity and magnetic field strength away from the galactic plane (this is, apparently, just the case with other galaxies[24,28])[9].

Thus, repeating to a certain extent the conclusion made at the end of section 7 one can say that the halo model has practically already been proved, though the parameters of the cosmic-ray and radio-haloes are yet to be specified.

9. Radio-astronomical data show that supernovae not only can, but do in fact, generate relativistic electrons with a high total energy reaching $W_{sn,e} \sim (1-3) \times 10^{48}$ erg per flare; this corresponds to the power $U_{sn,e} \sim W_{sn,e}/T_{sn} \sim 10^{39}$ erg/sec, where $T_{sn} \sim 30$ years $\sim 10^9$ sec is a mean time interval between supernova flares in the Galaxy. These figures are very rough estimates but they are to remind us of the repeatedly noted fact that supernovae can provide the necessary power to generate the electron component of cosmic rays. The same is true of all cosmic rays if they are assumed to be accelerated 30 times more effectively than electrons. The latter is quite possible from energy considerations (energy output of supernova flares apparently attains values of $W_{sn} \gtrsim 10^{51}$ erg, from which the mean cosmic ray power is $U_{sn,cr} \lesssim W_{sn}/T_{sn} \gtrsim 10^{42}$ erg/sec). At the same time there is no doubt that we cannot yet determine the mean power of supernovae as cosmic-ray sources from direct observations. Thus the assumption that it is specifically supernovae that are the main cosmic-ray sources in the Galaxy remains unproved.[10] Besides what has been said, the discovery of pulsars, which are present at least in a part of supernova remnants and generate relativistic particles for a long time, clearly testifies in favor of this assumption. Comparison of supernovae with other active stars-novae, magnetic stars, etc., also gives clear evidence for the effectiveness of supernovae as cosmic-ray sources, in any case at energies higher than

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[9] A decrease in the field strength, particularly if it is accompanied by a decrease of cosmic ray energy density, need not at all have such a disastrous influence on the effectiveness of retaining the cosmic rays in the system as is considered in Ref. 27.

[10] The gamma-astronomical method can provide an insight into this question. Unfortunately, the available data[17] on enhanced gamma-radiation from regions close to young pulsars (and supernovae remnants) in Crab and Vela do not allow us to extract the fraction of radiation due to cosmic-ray collisions in the gas (the bulk of gamma-rays is, apparently, generated in the pulsar magnetosphere). Note also that a possible difference between the energy spectra of the proton-nuclear and electron components generated in supernova remnants cannot serve as an argument against acceleration of both these components in the remnants (cf., Ref. 37).

10^9–10^{11} eV (i.e., for the bulk of cosmic rays). The only alternative which seems real for the Galaxy as a whole is cosmic-ray acceleration in flares of the galactic nucleus. There is, unfortunately, little data on the nucleus of the Galaxy but the last more or less powerful explosion took place there evidently about 10^7 years ago. This circumstance is very important: during the time of 10^7 years relativistic electrons of energy higher than 10^9–10^{10} eV (the estimate depends on the character of particle propagation) could not have reached the earth from the galactic centre because of losses.[33] Therefore explosions of the galactic nucleus cannot be the main source of all cosmic rays (including electrons) observed near the earth. However, it seems possible that the electron component originates for the most part in supernovae (including pulsars), whereas the bulk of the proton-nuclear component is generated in explosions of the galactic nucleus. Such a version developed by Ptuskin and Khasan[34] is undoubtedly of interest and can be verified in several ways (by the energy-dependence of the cosmic-ray lifetime T_{cr}, by the distribution of nuclei in cosmic rays with respect to their path in the interstellar medium, etc.). At the same time it should be emphasized that while the galactic nucleus is still a purely hypothetical effective cosmic-ray source, supernovae and pulsars can surely be regarded as such sources.

10. Summarizing one may note that development of high-energy astrophysics (it is apparently typical of science in general) proceeds rather unevenly. On the one hand during the last twenty five years brilliant and most important results have been obtained: clarification of the role of cosmic rays in the Universe, the birth of X-ray and gamma astronomy, to say nothing of a number of more concrete discoveries and achievements. On the other hand the same quarter century period turned out to be insufficient to obtain an entirely convincing answer to some fundamental and what might appear to be rather simple questions concerning the parameters of the galactic radio-halo, the mean age of galactic cosmic rays, and the role of different cosmic-ray sources, etc. If one turns to the history of cosmic-ray research which covers at least 65 years (beginning with the papers by Hess), one will not be very much surprised at this situation. But then the same evidence is provided by the history of the development of physics and astronomy.

I have emphasized all this because, in particular, I myself at one time expected more rapid progress in solving the problem of the origin of cosmic rays. Therefore in the last ten years, when one had to touch upon the origin of cosmic rays, some uneasiness was felt as to how long can the same things (the radio-halo, the age of cosmic rays, etc.) be discussed. Today we also are discussing these questions but clearly on the basis of essentially new material. I think that we can now assert that we are near the solution of the problem of the origin of cosmic rays "in first approximation." Simultaneously a number of questions has been formulated and is under consideration that can be regarded as pertaining to the "second approximation." They are the origin of cosmic rays of superhigh energy, measurements of anisotropy, study of the positron component, plasma and magnetohydrodynamic effects in cosmic rays, and the problem of the mechanisms of acceleration of cosmic rays, not to mention further investigations concerning the chemical and isotopic composition of cosmic rays, their energy spectrum, the electron component spectrum as well as radio-astronomical, X-ray and gamma-astronomical observations.

In making predictions the year 2000 is most often taken as a boundary mark. Here, of course, some "magic of numbers" makes itself felt—suffice it to say that the XXIst century does not begin in the year 2000 but on January 1, 2001. As concerns cosmic rays, the most natural mark is 2012, a hundred years from their discovery. We are separated from these dates by 23 and 35 years respectively. As has been mentioned already such a period seems psychologically to be very long especially for young people. But in the light of what has been said above it is clear that 20–30 years are not such a long period for the development of astrophysics and physics if one takes into consideration the great number of problems arising and the exceptional difficulties standing in the way of solving some of them. The questions and problems in the domain of high-energy astrophysics, which are already under investigation or have just been formulated, are in themselves sufficiently important, interesting and often fascinating. Therefore, even if no unexpected important discoveries are made in this field by the end of the century (one should not be expecting them continually) the prospects for the development of high-energy astrophysics in the nearest decades seem quite bright.

APPENDICES

The study of cosmic rays and also of cosmic X-ray and gamma radiation ranks high in modern physics and astrophysics. In order that the extent of the work should be more evident Appendix 1 briefly lists the contents of papers submitted to the 15th International Cosmic Ray Conference. The remaining Appendices 2–6 include some data and remarks on the origin of cosmic rays and, in general, on a number of problems to which the present paper is devoted.

1. On the 15th International Cosmic Ray Conference (Plovdiv, Bulgaria, August 1977)

Such conferences have already been held for 20 years (they are convened once every two years), they assemble hundreds of participants and are rather prolonged. Thus, about 350 participants were present at the 15th conference, it lasted two weeks, more than 800 papers were submitted and 9 invited lectures were also presented (the author's lecture was one of them) and 21 rapporteur talks were given.

At the beginning of the conference the participants were offered 9 volumes of materials[38] with brief summaries or abstracts of the submitted papers. These 9 volumes contain about 3500 pages. Three more volumes are to be published including papers which were submitted late, texts of invited lectures and rapporteur talks and also the reference material (table of contents, addresses of participants, etc.).

Volumes 1 and 2 contain reports (about 220)[11] on the origin of cosmic rays and related problems (section OG). Volumes 3 and 4 include reports on modulation and geophysical effects (MG, 180 papers), volume 5 is devoted to particles from the Sun (SP, 65 papers), volume 6—to muons and neutrinos (MN, 75 papers), volume 7—to high energies in a nuclear-physics context (HE, 135 papers), volume 8—to reports on extensive atmospheric showers (EA, 130 papers) and, finally, volume 9 consists of methodological papers (T, 60 papers). It is, of course, impossible to distinguish strictly between the subjects, and material in different sections partly overlapped. The subjects discussed in the OG section (origin of cosmic rays) and included in volumes 1 and 2 are already clear from the titles classifying the groups of papers:

1. Diffuse cosmic and galactic gamma rays.
2. Gamma-ray sources.
3. X-ray astronomy.
4. Gamma-ray bursts.
5. Nuclear composition of cosmic rays.
6. Isotopic composition of cosmic rays.
7. Electrons and positrons.
8. Origin and transport of cosmic rays.
9. Cosmic ray sources.
10. Cosmic ray interactions.
11. Implications of the composition of cosmic rays.
12. Siderial variations of cosmic rays.
13. Propagation of cosmic rays.
14. Cosmic rays of ultra high energy.
15. Composition of cosmic rays of low energy.
16. Miscellaneous.

As has already been emphasized, a number of papers pertaining to other sections (particularly to section MG and SP) is closely connected with the above mentioned topics which are in some cases rather arbitrary and appear somewhat indefinite. In our opinion it is, however, out of place to go into more detail—the task of the present Appendix is only to characterise in general the scale and trends of the investigations carried out at present. Neighboring regions, such as X-ray and gamma astronomy were presented at the conference far from completely. This concerns particularly X-ray astronomy which is developing rapidly and for the most part has already separated from physics and astrophysics of cosmic rays. Gamma-astronomy is still rather close to cosmic-ray astrophysics but it has also begun to extend in different directions and to be set somewhat apart. In particular, symposia devoted specifically to gamma-astronomy[16,17,39] have already been convened for several years. The last one[39] was held in May, 1977 in connection with new observations of the European gamma-satellite COSB; the papers submitted to this symposium make up about 400 pages and its results were partially presented in the rapporteur talk[40] together with the corresponding materials of the 15th cosmic ray conference. The following Appendix 2 is devoted to gamma-astronomy.

At the next 16th International Cosmic Ray Conference (it is to be held in Kyoto, Japan, in August 1979) the subjects will probably not undergo essential changes.

2. Some gamma-astronomical results

Gamma-astronomy is today the youngest branch of astronomy, it is only 10 years old (we have in mind directions in which positive experimental results have already been obtained; it is known that in neutrino astronomy and gravitational wave astronomy only upper limits are available for the corresponding fluxes). Nevertheless even the scale of existing observations, to say nothing of future projects and theoretical investigations, is impressive. Gamma-radiation from the galactic disc is observed (mainly in the energy range $E_\gamma > 35$ MeV and up to 1–2 GeV), some dozen discrete galactic gamma sources have been discovered, an isotropic (for the main part, probably, extragalactic) gamma-background is being measured; one should note particularly the ground observations (by the Cherenkov radiation in the atmosphere) of gamma-rays of energy $E_\gamma > 5\times10^{11}$ eV from some discrete sources. One can mention also the study of gamma-rays from the Sun and cosmic gamma-rays of nuclear origin. In this connection attention is first of all attracted to gamma-rays of an intensity I_{γ,π^0} which appear as a result of π^0-meson decay[12] and which are generated by the proton-nuclear component of cosmic rays. As has already been emphasized in this report observations of these gamma-rays are the basis of practically the only direct method of determining the cosmic-ray (proton and nuclear) intensity $I_{\rm cr}$ far from the earth. It has always been clear, of course, that bremsstrahlung and inverse Compton radiation generated by relativistic electrons may also contribute to the observed gamma-ray intensity I_γ; contribution from discrete sources, specifically from pulsars, is also possible. It seemed, however, that using observations in the energy range $E_\gamma > 35$–50 MeV and even with a rough determination of the spectrum (e.g., knowing the intensities $I_\gamma(E_\gamma > 100\text{ MeV})$ and $I_\gamma(E_\gamma > 50\text{ MeV})$) one could extract[16,17] the intensity I_{γ,π^0} reliably enough. New results are those obtained with the satellite COSB (cf., Ref. 38, OG-1 and Refs. 39, 40), which indicate that the spectrum observed for the region of the galactic disc differs from the one characteristic of π^0-meson decay (energies $E_\gamma < 30$ MeV are represented very little in this latter spectrum). If we assume that we are dealing with the combined radiation from π^0-meson decay and bremsstrahlung radiation, the role of the latter must be

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[11] All such figures are rounded off.

[12] The decay of the Σ^0-hyperon is in fact also taken into account but this channel is of secondary importance.

much higher than it was supposed to be before. The role of the inverse Compton radiation in the disc region is rather small but a possible contribution of discrete sources is the third component that must be taken into account.

One may hope to extract the contribution from discrete sources when the angular resolution is increased and the variable component is separated (first of all from pulsars). The determination of the contribution from bremsstrahlung radiation will evidently be possible only as a result of more accurate determinations of the spectrum, particularly at $E_\gamma > 100$ MeV. Here it is appropriate to mention the following.

Bremsstrahlung photons of energy E_γ are produced mainly by electrons of energy $E_e \sim E_\gamma$ (the electron spectrum here is, of course, considered to decrease with energy). But even at $E_e \lesssim 1$ GeV, to say nothing of the region of $E_e \lesssim 100$ MeV, the electron spectrum near the solar system is not very well known and one evidently cannot hope to obtain reliable data here. Besides, in remote regions both the shape of the spectrum and the value of the intensity of electrons of energy $E_e < 1$ GeV may prove to be different from those near the sun. Suffice it to say that just in the region of comparatively low energies electrons can, in principle, be accelerated effectively not only in explosions or remnants of supernovae but also by other stars (novae, flare stars, magnetic stars, etc.). On the other hand, neither can the region of electron energies $E_e < 1$ GeV be practically checked by radiodata. Indeed, the characteristic frequency ν_m at which an electron of energy E_e radiates, while moving in a magnetic field with a component $H_\perp$ perpendicular to the line of sight, is equal to

$$\nu_m = 4.6 \cdot 10^{-6} H_\perp E_{e,\,(\mathrm{eV})}^2 \qquad (1)$$

From this at $H_\perp = 2 \times 10^{-6}$ G and $E_e = 10^9$ eV the frequency $\nu_m \sim 10$ MHz. At lower frequencies radio-astronomical observations are almost not carried out at all, and besides it is hardly possible to pick out the synchroton component of the disc.

Thus, if COSB spectral data are reliable, extraction with confidence of the intensity $I_{\gamma,\pi 0}$ and, therefore, obtaining information on the proton-nuclear cosmic-ray component in the region of the galactic disc, require sufficiently accurate spectral measurements of the intensity $I_\gamma(E_\gamma)$ for $E_\gamma \gtrsim 0.5$–1 GeV. This will apparently be possible only for the next generation of gamma-telescopes. But at the same time by virtue of sufficient reliability attained in the calculation of the energy dependence in the spectrum of $I_{\gamma,\pi 0}(E_\gamma)$, the difference $I_\gamma(E_\gamma) - I_{\gamma,\pi 0}(E_\gamma)$ will also be determined for $E_\gamma < 0.5$ GeV. As a result, after separation of the contribution from discrete sources (this is probably quite possible) information will also be obtained concerning the cosmic-ray electron component far from the earth for energies $E_e < 1$ GeV. The importance of such information can hardly be overestimated.

The farther from the galactic plane (say, in observations for directions with galactic latitude $b > 10^0$), the smaller is the contribution of the disc component and, in principle, one may hope to record gamma-radiation from the halo. In this case gamma rays from π^0-meson decay[13)] and inverse Compton radiation from electrons must, in general, be taken into account. As is well know, under the condition

$$E_e \ll \frac{1}{4}\left(\frac{mc^2}{\varepsilon_{\mathrm{ph}}}\right) mc^2 \approx \frac{6 \cdot 10^{10}}{\varepsilon_{\mathrm{ph},(\mathrm{eV})}} (\mathrm{eV}) \qquad (2)$$

(here $\varepsilon_{\mathrm{ph}}$ is the energy of the photons, which scatter electrons of energy E_e, $\varepsilon_{\mathrm{ph}(\mathrm{eV})}$ is the photon energy in eV) the scattering may be regarded as classical and the mean energy of the gamma-photons produced is

$$E_\gamma = (4/3)\, \bar{\varepsilon}_{\mathrm{ph}}\, (E_e/mc^2)^2, \qquad (3)$$

where $\bar{\varepsilon}_{\mathrm{ph}}$ is the mean energy of photons distributed isotropically with respect to directions. Even for star light, when $\bar{\varepsilon}_{\mathrm{ph}} \sim 1$ eV, condition (2) is fulfilled for the greater (in terms of intensity) part of the electron spectrum; this is all the more valid for relict photons with $\bar{\varepsilon}_{\mathrm{ph}} \lesssim 10^{-3}$ eV. Therefore using formula (3) we see that in scattering by star light the main part of gamma radiation corresponds to energy $E_\gamma \lesssim 100$ MeV (we assume $E_e \lesssim 5 \times 10^9$ eV); in the case of scattering by relict photons we deal with energies $E_\gamma \lesssim 0.1$ MeV which belong already to the X-ray range.[14)] From published calculations[41,42] it follows that the inverse Compton gamma-radiation from the galactic halo can prove to be considerable. A more or less reliable determination of the corresponding intensity is, however, possible only when radio-astronomical data are used and, specifically, the

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[13)] Since the cosmic-ray halo is bigger than the radio-halo and the gas density in the halo is not well known (probably $\bar{n} \lesssim 10^{-3}$ cm^{-3}) there is no reason to neglect this component in advance.

[14)] Measurements of the intensity of X-rays produced by inverse Compton scattering by relict radiation make it possible to determine the density of relativistic electrons generating the X-rays (the relict radiation temperature is, of course, considered to be known, i.e., equal to 2.7 °K for the cosmologically close sources). If a given source (or its neighborhood), or more precisely the same relativistic electrons in the source, are also emitting synchroton radiation, then combining the radio and the X-ray data one can, in principle, obtain also the magnetic field strength in the source (e.g., on the assumption that this field is on the average isotropic with respect to direction and, therefore, on the average $H_\perp^2 = 2H^2/3$, where $H_\perp$ is the component of the field H perpendicular to the line of sight). Such a method has already been successful[65] in the case of the radio-galaxy Centaurus A (Cen A) closest to us (at a distance $R = 5$ Mparsec). The mean value of the field was estimated here to be equal to $H \approx 7 \times 10^{-7}$ Oe. The energy density $H^2/8\pi$ of such a field is approximately equal to the energy density of all cosmic rays in the source if we assume that they contain equal numbers of protons and of electrons (in other words if $w_{\mathrm{cr}} = 2\, w_{\mathrm{cr},e}$ or $\varkappa_r = 2$, then $w_{\mathrm{cr}} \approx H^2/8\pi$, i.e., $\varkappa_H \sim 1$). At the same time, as we know, for cosmic rays near the earth $\varkappa_r \sim 10^2$. On the other hand information on the radioemission spectrum indicates that in Cen A electrons are accelerated in the radio-clouds themselves,[65] and not in the stellar galaxy. That is why when estimating the parameter $\mathcal{K}_r$ there are no particular grounds to rely upon the analogy with our Galaxy. We also note that the estimate of $\varkappa_r$ is altered if the strong inhomogeneity of the magnetic field in the radiating region is taken into account.

relativistic electron density $N_e(E_e)$ in the halo obtained from these data (Ref. 15). If the corresponding gamma-ray intensity $I_\gamma(E_\gamma)$ due to the inverse Compton scattering will prove to be sufficiently significant, one may hope to separate the gamma-radiation from the halo from the isotropic metagalactic background taking into account its anisotropy (dependence on the galactic coordinates l and b) and also its spectrum. In this case questions also, of course, remain of taking into account the disc component, the discrete sources and, finally, the abovementioned possible contribution of gamma-rays from π^0-meson decay.

We emphasize that even the available data on galactic gamma-radiation are very important for the problem of the origin of cosmic rays. Indeed, they in any case, give an upper limit on the intensity $I_{\gamma,\pi^0}(E_\gamma > 100$ MeV). From this no far-reaching conclusions can yet be drawn concerning a strong inhomogeneity in cosmic ray (proton and nuclear) density distribution in the disc, particularly in the direction toward the galactic center. However, the conclusion about the decrease of cosmic-ray density in the direction towards the anticenter seems more convincing. The conclusion[43] concerning the decrease in the energy density w_{cr} with distance from the central galactic region and, therefore, concerning the lack of validity of metagalactic models of cosmic-ray origin apparently finds confirmation in the same arguments (cf., the text of this report and Refs. 21, 22).

Thus, gamma-astronomy has already made a contribution to the solution of the problem of the origin of cosmic rays and promises still much more data of different kinds. Besides the prospects made clear by what has been said above we note the possibility of determining the amount of cosmic rays in supernovae remnants and near them. The available data[17,39] make it possible to establish only an upper limit on the total energy of cosmic rays produced in a supernova explosion (and retained in the shell or in its vicinity). For the shell in Vela this limit apparently corresponds to a value of not less than 10^{50} erg. At the same time the required cosmic-ray generation power in the Galaxy $U_{cr} \sim 3\times10^{40}$ erg/sec demands (if supernovae appear on the average once in $T_{sn} = 30$ years[15)]) on the average the production per supernova of cosmic rays having a total energy $W_{sn} = U_{cr}T_{sn} \sim 3\times10^{49}$ erg. From the nature of this estimate this value may turn out to be an overestimate; moreover, we are dealing with an average value. Therefore an observation in some shell of cosmic rays with total energy exceeding approximately 10^{49} erg will confirm the hypothesis concerning the effectiveness of supernovae as sources not only of the electron but also of the proton-nuclear component of cosmic rays. But if in some particular shell the cosmic-ray energy is less than, say, 10^{49} erg, this proves almost nothing at all. As has already been said, at present we still do not have even such data at our disposal and therefore have no gamma-astronomical arguments against the choice of supernovae as the principal cosmic-ray sources in the Galaxy.

3. The problem of the halo and the choice of the model of the origin of cosmic rays

As a supplement to the main text it should be stated that observations[45] of galaxy NGC 4631 using wavelengths of 6.25 cm and 11 cm only confirm the picture established in Ref. 28a for longer waves (cf., Figs. 1 and 2). For our Galaxy when the calculations[46] carried out on the basis of a diffuse halo model are compared with radioastronomical data they are found to be in general agreement with the results of Refs. 25, 26 (cf., also Ref. 15) which gives evidence for the presence of a rather powerful and extended radio-halo (thus, according to Ref. 46, at a frequency of 17.5 MHz the radio-halo half-thickness, corresponding to a two-fold decrease in intensity, is equal to 3 kparsec; this corresponds to a value of the halo half-thickness up to its conventional boundary of $h_h \sim 6$ kparsec). On the whole it is evidently no longer possible to doubt the existence of a radio-halo.

What is the role played by measurements of the amount of the radio-active isotope ^{10}Be in the solution of the halo problem? In connection with numerous and so sometimes incorrect remarks on this topic repeated in the literature something should be added to what has already been stated in this respect in the main text of this report. According to the latest data[47] an analysis of the results of measurements of the amount of ^{10}Be on the basis of a homogeneous model leads to the values of $T_{cr}^{(hom)} = 1.7\times10^7$ years and a mean gas density of $\bar{n} = 0.2$ cm^{-3}. Such density corresponds to a region (disc) of half-thickness $h_{^{10}Be} \sim 1000$ parsec $\sim 3\times10^{21}$ cm. This indeed proves that ^{10}Be nuclei are present not only in the gaseous disc but also in a region thicker by an order of magnitude. However, it by no means follows from this that stable nuclei also occupy a similar, rather than a much larger, region referred to as a cosmic-ray halo. We may hope that this circumstance is explained in sufficient detail in Refs. 15, 29, 30. With the use of the diffusion approximation the above values of $T_{cr}^{(hom)}$ and $h_{^{10}Be}$ make it possible to conclude that the corresponding diffusion coefficient D determined from the relation $h_{^{10}Be} \sim (2DT_{cr}^{(hom)})^{1/2}$ is equal to $D \sim 10^{28}$ cm^{2}sec^{-1}. Such an estimate for a region near the galactic plane is quite reasonable and does not contradict the estimate $D \sim 10^{29}$ for the halo as a whole.

As has been repeatedly emphasized (see, particularly, Ref. 10) the diffusion picture and correspondingly the use of the diffusion equation in application to cosmic-ray propagation in galaxies (and generally under cosmic conditions) is at best an approximation. We may hope that such an approximation is sufficiently good for the Galaxy "in the large," i.e., for significant regions and for sufficiently long time intervals. Large dimensions in space and time are essential here because under such conditions there is good reason to consider cosmic rays to be "mixed" and their distribution in space to be smoothed out. In this case the diffusion coefficient D must be regarded as a free parameter chosen from comparison with observations. The next step is taking into

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[15)] According to the most recent data[44] the average time between supernova flares in the Galaxy is $T_{sn} = 11^{+14}_{-4}$ years.

account the dependence of D on the coordinates (in the simplest case different values of D can be chosen in the gas disc and in the halo) and possibly also on direction ($D_\parallel$ for diffusion along the disc and $D_\perp$ for diffusion from disc to halo).

If diffusion models are used as a basis one must try to determine the maximum possible number of quantities within the framework of one and the same model. In principle calculations should be compared with observed radio-astronomical data, with information about the intensity $I_e(E_e)$ of the electron component and about the chemical and isotope composition of cosmic rays, and in future also with the results of measurements of the positron component intensity $I_{e+}(E_e)$ and with gamma-astronomical data (at present the available information apparently imposes only very slight restrictions on the choice of the model). A measurement of antiproton intensity would be also very valuable but it is not clear whether this will be possible in the near future.

As far as the domain and the conditions of applicability of the diffusion approximation are concerned, much can probably be gained from investigations devoted to cosmic ray propagation in the solar system.[48] Beyond the limits of the diffuse approximation lies the compound diffusion model. Here it is not clear, however, whether the basic concepts are valid, neither is it easy to distinguish between this model and the usual diffusion approximation.[49] Another possibility is to take both diffusion and convection into account.[50] In the simplest case of one-dimensional propagation in a region external to the sources the diffusion equation for protons and nuclei (with a constant D) has the form

$$D\frac{d^2N}{dz^2}=0. \tag{4}$$

Under the same conditions, but in the presence of convection with a constant velocity V the particle density N is determined by the equation

$$D\frac{d^2N}{dz^2}-V\frac{dN}{dz}=0. \tag{5}$$

The solution of Eq. (4) has the form $N=Az+B$, while from Eq. (5) the density is given by

$$N=A'e^{(V/D)z}+B'=A'+A'\frac{V}{D}z+\frac{A'}{2}\left(\frac{V}{D}z\right)^2+\ldots+B'.$$

From this it is clear that for a region (halo) of dimension h the role of convection is determined by the term

$$\frac{A'}{2}\left(\frac{Vz}{D}\right)^2\leqslant\frac{A'}{2}\left(\frac{Vh}{D}\right)^2,$$

which should be compared, say, with the sum $A'+A' \times (Vh/D)<1$ exceeds the convective term by at least a factor of four. In general, as is clear also from more general considerations, convection changes the picture significantly only for $Vh/D>1$ and practically probably only under the condition that $Vh/D\gg 1$. The values of the "galactic wind" velocity V cannot be very high—otherwise the Galaxy would lose too large a mass, etc. If according to Ref. 50 we assume the value $V\sim 3\times 10^6$ cm/sec then for $D\sim 10^{29}$ cm^2/sec and $h\sim 3\times 10^{22}$ cm the parameter $Vh/D\sim 1$. Under such conditions for the greater part of the halo (for $z<h$) convection will not be important, while the region near the conventional halo "boundary" in general requires further investigation. On the whole, there are no grounds so far for objecting to convection being taken into account, but it is also untimely to insist upon its importance. Progress in this question can probably be made only after obtaining more accurate values of the velocity V from independent astronomical data.

The solution of the diffusion equation is often based on one-dimensional models which take into account only diffusion perpendicular to the galactic plane.[15,50] It is quite obvious that this is not always possible. In particular, if there exists a considerable increase of cosmic ray density in a ring-shaped region around the galactic center with radius of about 5 kparsec,[16,17] gamma-astronomical observations must be treated on the basis of at least a two-dimensional model already in the first approximation. This is just what is done in Ref. 51 where from comparison with observations it is concluded that the characteristic halo dimension is $h<5$ kparsec. Even such a result does not in our opinion contradict the halo model. What is more important, the marked increase in cosmic-ray (protons and nuclei with $E>1$ GeV/nucleon) density appears to be unproved, particularly in view of the data of Ref. 39. On the whole gamma-astronomical data are not yet sufficiently accurate and reliable to arrive at quantitative conclusions concerning halo dimensions.

We shall make one more general remark in connection with the discussion of galactic models describing cosmic-ray propagation. In choosing such a model we were guided mainly by the picture "in the large" observed with a radiotelescope. These results may be extended to cosmic rays observed near the earth only under additional assumptions, i.e., in the presence of sufficiently good mixing and averaging of cosmic rays in the Galaxy. Smoothness of radio isophotes (cf., in particular, Figs. 1–3), various theoretical arguments and a high degree of cosmic ray isotropy testify in favor of this assumption. Indeed, if cosmic rays entered the solar system only from a small region or even along one extended "tube of force" of the magnetic field, it would be natural to expect considerable anisotropy. But in the presence of mixing a high degree of cosmic ray isotropy (at $E<10^{15}$–10^{17} eV) is quite natural (cf., e.g., Refs. 10, 15).16) Therefore it seems quite probable that the diffusion galactic halo model is quite suitable not only for the analysis of radioastronomical data but also in application to calculations of the characteristics of all the components of primary cosmic rays near the earth. The latter assertion has not yet been proved and this led to the discussion of other models. We mention here "closed"[52] and "semiclosed"[53] galactic models. We regard both these models, as well as the homogeneous (leaky box) model, as being inconsistent (or at least incomplete) because of the disregard to the requirements following

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16)The character of the magnetic field near the solar system must affect from this point of view only the direction in which the cosmic-ray intensity is maximal.

from radioastronomical observations. But since Refs. 52, 53 make certain predictions concerning the primary cosmic rays near the earth, verification of these predictions can only be useful. But even agreement between calculations and experiment will not in itself prove the validity of the corresponding models, since the same conclusions might also turn out to follow from the diffusion-galactic models with a halo as in the case of the homogeneous model (see Ref. 15).

For progress in studies in the field of the origin of cosmic rays and of high-energy astrophysics as a whole it is very important to limit the class of possible models as far as possible. The opinion of the present author in this connection is clear from what has been said above.

4. On acceleration of cosmic rays in supernova remnants

Supernovae as cosmic ray sources have attracted attention[2] from energy considerations and in any case before the appearance of astronomical data testifying in favor of generation of high-energy particles in supernovae. The discovery of synchrotron radioemission from supernova remnants has proved that such generation does take place.[8–10] However questions about generation mechanisms and concerning the relative importance of supernovae in generation of different particles determining the cosmic-ray composition over the whole energy range remain to a considerable extent open up to now.

Particle acceleration in supernovae may proceed in at least three ways, one can say along three channels. Firstly, in the presence in the shell of turbulent motions (and they are observed in the shells) statistical acceleration (the second-order Fermi acceleration mechanism)[3] appears to be very effective.[54] Secondly, acceleration may take place in a shock wave in the supernova explosion[55] itself. And thirdly, since 1967–68, when pulsars were discovered, the possibility of particle acceleration near a pulsar or under the influence of its low-frequency radiation has been discussed. The present state of the problem of acceleration in supernovae is described in Ref. 56 and here I would like to make only some remarks in this connection.

The cosmic-ray spectrum has a power dependence ($I_{cr}(E)=KE^{-\gamma}$) with a constant index $\gamma\approx 2.7$ over a very large energy range from 10^{10} to 10^{15} eV. It is difficult to believe that such a result is accidental and it is natural to suppose that the above form of the spectrum either reflects some general features of the acceleration mechanism or points out the presence of a dominating source (e.g., one located in the galactic center); however, if sources of one kind are meant (e.g., supernovae of the II kind), the constancy of γ is also easier to explain than under the assumption of action of different types of sources. Although this problem has long been under discussion[10,37,58] it is in general not yet solved and is actually a fundamental one.

We cannot say the same about discussions of the problem of adiabatic energy losses which can occur during expansion of supernova remnants. We can come across statements in the literature that adiabatic losses are surely essential and force us to increase considerably the energy demanded in supernova explosions etc. Meanwhile adiabatic losses in supernova remnants equivalent to the first-order Fermi-acceleration (deceleration) were already considered long ago[57] and, what is essential, they may be overcome in a number of different ways. In the simplest version discussed in Ref. 57 the change in particle energy due to statistical acceleration and expansion is determined by the equation

$$\frac{dE}{dt}=\frac{\Delta E}{\tau}=\beta E\sim\left(u^2-\frac{avVl}{r}\right)\frac{v}{lc^2}E, \tag{6}$$

where $\tau=l/v$ is the time between particle collisions (particle velocity is v) with scattering (reflecting) clouds or filaments (mean distance between them is l), u and V are respectively the velocities of random and regular motions of clouds, r is the shell radius and a is a coefficient of the order of unity. Already from (6) it is clear that statistical acceleration (for which $\beta=\beta_{II}\sim u^2v/lc^2$) may easily exceed adiabatic deceleration (in the presence of only this deceleration $\beta=\beta_I\sim -v^2V/c^2r$). In more complicated models there are even more parameters and it is difficult to establish reliably the sign of β, i.e., the rate of acceleration or deceleration: this may be accomplished convincingly only by using specific information about a given shell. As has been emphasized already in Ref. 57 conditions in the envelope of Cas A are particularly favorable for acceleration even in our epoch (to say nothing of earlier stages). Modern data and estimates[58] confirm this conclusion taking also into account the observed decrease in the flux of radioemission from this remnant. Unfortunately the latter conclusion is merely mentioned in Ref. 56 (the corresponding paper has not yet been published). At the same time it is already clear from general considerations that a decrease in the flux of radioemission is in principle possible also under conditions of continuing acceleration of electrons, to say nothing of protons and nuclei. In Cas A a temporary increase of radio-emission flux has been observed,[58] i.e., a monotonic decrease does not take place at all. Adiabatic losses may be unessential also in the models considered in Refs. 59, 60.

In general there are no weighty objections at all to the assumption about the dominating role of supernovae as cosmic ray sources, but neither has it been proved. In this connection we would like to mention an interesting remark[61] concerning the necessity to take into account the discreteness of cosmic ray sources in calculations of the spectrum of electrons of sufficiently high energy; as a result of a certain limitation on the number of active cosmic ray sources may be obtained. It is not yet clear in advance, of course, whether or not supernovae will satisfy appropriate requirements.

5. Cosmic rays of superhigh energy

Superhigh energy cosmic rays (SHECR for short; it is assumed somewhat arbitrarily that their energy is $E>10^{17}$ eV) may prove to be not so closely associated with the bulk of cosmic rays near the earth. Specifically, it is not excluded that some peculiar extragalactic component is involved. In any case the study of SHECR is a special problem. The present state of this problem is described in Ref. 62.

SHECR may be considered to be of galactic origin only under the assumption of the existence of an extended halo with a regular magnetic field (more precisely, with a field that has a regular component). Moreover, cosmic rays with $E > (1-3)\times 10^{19}$ eV cannot be protons but must consist of medium or heavy nuclei. A certain anisotropy must also be observed. But if SHECR are of extragalactic origin, the sources must be supernovae or nuclei of Syfert galaxies which are in a Local Supercluster. An intermediate situation is, of course, also possible when particles with $10^{17} < E \lesssim 10^{19}$ eV are produced in the Galaxy and with $E \gtrsim 10^{19}$ outside it. There is no reason to present here in greater detail the contents of Ref. 61, we wanted only to emphasize that SHECR present a separate problem. This refers not only to the origin of SHECR and to their characteristics but also to the fact that in the forseeable future there is no hope of obtaining such particles (or their equivalent in a transition to the center-of-mass frame of reference) under laboratory conditions.

6. Concluding remarks

In spite of the fact that these appendices are almost as extensive as the report itself, we managed to cover only a small part of the material discussed at the 15th International Cosmic Rays Conference. In particular, we have not touched upon rather numerous new data on chemical and isotopic composition of cosmic rays and also on the spectrum of the electron component.[17] Nevertheless, it may be hoped that the above material will allow the reader to acquire a certain overview of the present state of the problem of the origin of cosmic rays. The tasks of further investigations are also sufficiently clear. As for real prospects of their successful solution, one should bear in mind the following. Although high-altitude balloons are still being used and will be used successfully, the broad scale of the study of primary cosmic rays and also of cosmic gamma-radiation belongs to satellites and particularly to heavy ones. Planning and carrying out such experiments takes many years. A lot of time is also needed to obtain data and to analyze them. Therefore only in about ten years may one hope to utilize in full measure the material which will be obtained in a number of experiments being planned now to be carried out with the aid of the next generation of satellite equipment. One may think that as a result only "high energy astrophysics of the nineteen nineties" will possess sufficiently full information concerning all the components of cosmic rays of energies up to $10^{12}-10^{14}$ eV or up to $10^{12}-10^{13}$ eV/nucleon. New specific problems will also, of course, appear, cosmic rays of superhigh energy will be studied, etc. But on the whole a certain conservative attitude to subject matter, if we may say so, seems to be natural and understandable over the next decade. An essentially new direction, the appearance of which can be foreseen, is neutrino astronomy (observations being carried out now on the flux of solar neutrinos are of outstanding importance, of course, but the birth of neutrino astronomy is understood to imply the obtaining of positive results–information about neutrino fluxes and not only about upper limits on them). The establishment of a neutrino station of the Academy of Sciences of the USSR, the realization of the DUMAND-project and of some other projects will permit recording of cosmic neutrinos from various sources and in particular of those coming from supernova remnants.[63,64] In this respect as well as in a number of others, neutrino astronomy is directly related to the problem of the origin of cosmic rays.

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