Astrophysical aspects of cosmic-ray research (first 75 years and outlook for the future)[1)]

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(Invited talk at the 20th International Cosmic Ray Conference, Moscow, 2–15 August 1987) The basic topics discussed here are the primary cosmic rays near the earth, cosmic rays in the universe, the origin of cosmic rays, a galactic model with a halo, and some prospects for future research.

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1. INTRODUCTION

Cosmic rays were not discovered in any single experiment. On the contrary, the existence of cosmic rays—high-energy charged particles—was established as the result of prolonged studies which date back to the first decade of the present century. It was not until 1927–8 that the last remaining doubt that penetrating radiation—cosmic rays—is reaching us from space finally died out. Nevertheless, we can somewhat arbitrarily set the date of the discovery of cosmic rays as 7 August 1912, when Victor Hess made his most successful balloon flight. The results demonstrated convincingly that the ionization rate of air in hermetically sealed vessels increases with altitude above the earth's surface (above 2 km or so). On the flight at an altitude of about 5 km on 7 August 1912, the ionization rate increased by a factor of severalfold. It could thus be said that the present conference is being held precisely 75 years after the discovery of cosmic rays. This span of time, while extremely long on the scale of a human lifetime, has not been long enough for a comprehensive study of cosmic rays—as is expressed eloquently by the rich program of this conference. Cosmic rays are not, of course, anything exceptional in this regard. Superconductivity, for example, was discovered in 1911, and today research on it is not only continuing but in fact expanding, becoming wider and deeper, so to say. The situation is shown clearly by the prominent event which occurred in 1986–7: the discovery of high-temperature superconductivity. (Incidentally, the present conference on cosmic rays will be followed immediately by an equally representative conference in Japan: the 18th International Conference on Low-Temperature Physics. One might say that cosmic rays and low temperatures are of the same age.)

Reseach on cosmic rays can be divided somewhat crudely into two directions or branches: astrophysics and nuclear physics. There was a stage in which the second of these directions was particularly important: research on cosmic rays for solving problems of elementary particle physics. The situation can be summarized by noting that it was in cosmic rays that positrons, muons, the $\pi^{\pm}$ mesons as well as certain other particles were discovered. Today, cosmic rays are still far from irrelevant to high-energy physics. For example, the ANI installation (the abbreviation stands for the Russian words for "hadron-nucleon research") is presently being constructed on Mt. Aragats in the USSR for research on the interaction of particles with energies E above 10^{15} eV and ranging up to 10^{18} eV. Such energies are presently unattainable at accelerators. This installation is to come on line in 1989. Nevertheless, beginning in about the 1950s, the astrophysical aspect or, as I will say, "cosmic-ray astrophysics," has been assuming a progressively more prominent place. This direction includes research on the primary cosmic rays (for the most part, observed near the earth)[2)] and the problem of their origin (acceleration in sources, the propagation of cosmic rays in the local galaxy and outside it, solar cosmic rays, etc.). At present, as is clear from simply the conference program (see the Supplement), γ-ray astronomy is also closely related to cosmic-ray astrophysics.

My report has been conceived as an introduction, addressed to not only the main participants of the conference but also the guests. Furthermore, I will not even attempt to list all the questions which are pertinent to the astrophysics of cosmic rays (charged particles) or to the fields of radio astronomy, x-ray astronomy, γ-ray astronomy, and also the astronomy of high-energy neutrinos, which are all related to some extent to cosmic-ray astrophysics. Furthermore, we cannot go into a detailed discussion of the history of research on cosmic rays here (see Refs. 1–3). It is nevertheless pertinent to point out some milestones along this long path (we are discussing only the astrophysical aspect).

1912. The discovery of cosmic rays (as qualified above). In the early stage of research on cosmic rays (for about 15 years), it was not totally certain that the observed radiation was of a nonterrestrial origin. Independently, it was assumed that the question was one of hard γ rays.

1927. By this time, doubt regarding the existence of a well-penetrating "radiation" (cosmic rays) coming from space finally died out. Indications of the presence of a latitude effect (a dependence of the ionization rate on the geomagnetic latitude) appeared. It accordingly became clear that the primary cosmic rays (the particles which are inci-

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dent on the atmosphere from space) are, at least in part, charged particles.

1936. At about this time it was finally recognized that cosmic rays were charged particles.

1939. It was established that cosmic rays have a positive charge and consist primarily of relativistic protons.

1948. The nuclei of several elements were observed in cosmic rays. In the same period (up to 1951–2) it was established that the flux of electrons in cosmic rays amounts to less than about 1% of the total flux. (Incidentally, electrons in the primary cosmic rays were first detected only in 1961.)

It was thus not until 40 years or so after the discovery of cosmic rays that their composition near the earth was finally learned, and then only in a first approximation. With regard to the sources of cosmic rays and in general with regard to cosmic rays far from the earth, however, essentially nothing was known until 1950, when the relationship between the electron component of the cosmic rays and the nonthermal cosmic radio emission was established. One might say that before this time cosmic rays were in the realm of physics and were stuied exclusively by physicists. It thus does not seem to me to be an exaggeration to establish the following historical milestone:

1950-1953. The birth of cosmic-ray astrophysics. Since the nonthermal cosmic radio emission is primarily of a synchrotron nature—i.e., is emitted by relativistic electrons (the electron component of the cosmic rays) moving in magnetic fields in space—two very important circumstances became clear. Firt, the electron component is present in intergalactic space, in the envelopes of supernovae, and in other galaxies. It is natural to suggest that the same comment applies to the main component of the cosmic rays: protons (or, more generally, nuclei). Second, estimates indicate that cosmic rays are an importnat factor from the energy and dynamic standpoints in these regions (the interstellar medium, the envelopes of supernovae, etc.). Cosmic rays have thus "entered" astronomy along with other astronomical objects: galaxies, stars, the interstellar gas, etc.

1953. Radio-astronomy data provided a foundation for an idea regarding the origin of the cosmic rays observed near the earth. This idea had also been discussed to some extent previously. A galactic model with a halo was proposed and developed. In this model, the galactic cosmic rays fill a large region (the "cosmic-ray halo") surrounding a galactic disk, and their main sources are supernova explosions (see Refs. 4 and 5 and the discussion below for more details).

It has now been 34 years since that data (1953), and I regard a halo galactic model as the most probable model and the model with the firmest foundation. Nevertheless, not everything on which this model rests has been reliably proved (the size of the cosmic-ray halo is not really clear, and we are not yet completely convinced that supernova explosions play a dominant role as sources of cosmic rays). Consequently, as we have often seen (and continue to see) in physics and astronomy, the problem of the origin of the cosmic rays (specifically, we are thinking of the choice of a model) has turned out to be a "tough nut," and there are a large number of difficulties which prevent reaching completely reliable conclusions. On the other hand, much has already been learned, and the paths to future progress have been defined fairly well. We will return to this topic below. At this point we wish to direct the reader to Table I. which illustrates (schematically) the field of research which falls in the category of cosmic-ray astrophysics. Also listed in Table I are certain branches of astronomy which border directly on cosmic-ray astrophysics. We are of course not thinking of the entire field of radio astronomy but only the radio-astronomy research which provides information on the cosmic rays in various parts of the universe. A similar comment could be made regarding the other fields of astronomy listed in this table. With regard to high-energy neutrino astronomy (we are thinking of the detection at the earth of neutrinos with energies above, say, 10^{12} eV, which are generated in space by cosmic rays), we should also point out that real measurements have not yet been carried out, and we are unfortunately dealing with only small installations and plans at this point. The last of the, shall we say, up-and-running branches of astronomy, and one of particular interest to research on cosmic rays, is γ-ray astronomy.

The detection of cosmic γ rays obviously provides information about the cosmic rays in those cases in which the latter generate γ rays in nuclear collisions and in other ways. Corresponding ideas appeared as early as 1952 and 1958, and the first observations (on balloons) were published in 1962 (see the bibliographys in Ref. 4). However, only the gamma satellites SAS II (1972) and COS-B (1975) provided a substantial amount of information about cosmic γ rays with energies 35 MeV $< E_\gamma <$ 5 GeV. Data of specifically this type are particularly important for research on the proton-nuclear component of the cosmic rays far from the solar system (we are thinking primarily of the γ rays produced in the decay of π^0 mesons). Nevertheless, the results

TABLE I. Cosmic-ray astrophysics (objects, problems, relationships).

1) *Primary cosmic rays at the earth*: Chemical (elemental) and isotopic compositions Energy spectra of protons and nuclei Electrons and positrons (e^+) Antiprotons ($\bar{p}$) Anisotropy of cosmic rays (δ)	2) Cosmic rays in the local galaxy, in supernova envelopes, in other galaxies, and in quasars Sources of cosmic and γ rays (in particular, The Cyg X-3 problem)	3) Radio astronomy Optical and x-ray astronomy γ-ray astronomy High-energy neutrino astronomy
5) Solar cosmic rays Propagation of cosmic rays in the solar system; variations of the cosmic rays	4) Origin of the cosmic rays Galactic model with a halo Propagation of cosmic rays in the interstellar medium Mechanisms for the acceleration of cosmic rays	

obtained on these two satellites were only first steps, and they did not provide clear answers to certain extremely important questions (e.g., the gradient of the cosmic-ray density in the local galaxy). Despite the obvious important and promising outlook for γ-astronomy research, it has now been 5 years (since 1982) that we have had any gamma satellite working. This is a sad page in the history of physics and astronomy, particularly in view of the fact that we need to try to observe γ radiation from the supernova explosion which occurred in the Large Magellanic Cloud in February 1987.

The appearance of γ astronomy (which can be dated somewhat arbitrarily as having occurred in 1972) is the last important milestone in the research on cosmic rays which we can identify here.

In summary, it has now been 75 years since the discovery of the cosmic rays. A lot has been done (see, in particular, Ref 6) but there are many problems, visible and clear, which await solution. New problems will of course also arise.

It would of course not be possible to cover in this report the huge amount of material which has already been accumulated. In §2 below, we attempt to outline what is known about the cosmic rays which are seen near the earth. In §3 we discuss some data on cosmic rays in the universe, obtained by radio-astronomy and γ-astronomy methods. In §4 we discuss the origin of cosmic rays and, in particular, the halo galactic model. In §5 we attempt to list the most important problems for future research on cosmic rays for roughly the next 25 years, i.e., up to the centennial of the discovery of cosmic rays.

2. PRIMARY COSMIC RAYS NEAR THE EARTH

Cosmic rays can be characterized most comprehensively by the differential intensity $I_{Z,A}(\mathbf{r},E,\theta,\varphi)dE$, expressed as the number of particles with energies in the interval $(E+dE,E)$ which pass per unit time through a unit area perpendicular to the obervation direction. The units for I might be, for example, the number of particles per square centimeter per second per steradian per energy interval. In this expression, Z is the atomic number (charge) of the nucleus, A is its mass number, $\mathbf{r}$ is the observation point, $E=E_k+Mc^2$ is the total energy ($M=AM_p$ is the mass of the nucleus, and M_p is the mass of a proton), and the angles θ and φ specify the observation direction. If one is not concerned with solar cosmic rays, and if the effect of the geomagnetic field is assumed to have been eliminated, then one can say that the primary cosmic rays are highly isotropic. The dependence of θ on φ is thus usually ignored, and the anisotropy is characterized by a coefficient δ which we will introduce below. Near the earth we are thus dealing with an intensity $I_{Z,A}(E)$ or, for the electron-positron component, $I_{e^\pm}(E)$. Also used is the integral intensity

$$I_1(>E)=\int_{E_{\min}}^{\infty} I_1(E)\,\mathrm{d}E,$$

where the index i is obviously Z, A, $e^{\pm}$, etc. Finally, the isotopic composition is by no means always determined; quite frequently, especially at high energies, the various elements are not distinguished either. The intensities $I_Z=\sum_A I_{Z,A}$ and $I=\sum_{Z,A} I_{Z,A}$ are accordingly used. For isotropic radiation, the flux of particles from a hemisphere of directions is

$$F_i=\int I_i\cos\theta\cdot\sin\theta\,\mathrm{d}\theta\,\mathrm{d}\varphi=\pi I_i$$

(the intensity I is frequently call a "flux" in the literature), and the density of particles having a velocity v_i is $N_i=\frac{4\pi}{v_i}I_i$. The energy density of the cosmic rays is

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

and the "energy intensity" is

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

For cosmic rays near the earth (outside the range of the geomagnetic field), we can also illustrate the situation with values referring to all cosmic rays:

$$\begin{aligned}
&I_{\mathrm{cr}}\sim 0.3-0.3\ \text{particle}/(\mathrm{cm}^2\cdot\mathrm{s}\cdot\mathrm{sr}),\\
&N_{\mathrm{cr}}\sim\frac{4\pi I_{\mathrm{cr}}}{c}\sim 10^{-10}\ \text{particle}/\mathrm{cm}^3,\\
&w_{\mathrm{cr}}\sim 10^{-12}\ \mathrm{erg/cm}^3\sim 1\ \mathrm{eV/cm}^3,\\
&J_{\mathrm{cr}}\sim\frac{cw_{\mathrm{cr}}}{4\pi}\sim 10^{-3}\ \mathrm{erg}/(\mathrm{cm}^2\cdot\mathrm{s}\cdot\mathrm{sr}).
\end{aligned}\tag{1}$$

Because of modulation effects, the intensity of cosmic rays in the energy region $\mathscr{E}_k=E_k/A\lesssim 1$ GeV/nucleon in the solar system varies with the solar activity, in particular, over the solar activity cycle. For this reason, the values listed above, which correspond to energies $E_k\gtrsim 100$ MeV, are simply indicative (the maximum in the proton spectrum corresponds to an energy $E_k\sim 250$ MeV, and all the integral quantities converge). It is clear from (1) that a flux $F\sim 1$ particle/(cm^2·s) arrives at the earth. About 90% of this flux (in terms of the number of particles) is protons (p). The number of ^{4}He nuclei is smaller by a factor of about ten, and the total flux of all heavier elements is about 1%. Essentially no primary protons, not to mention nuclei, reach the surface of the earth (at sea level). In the atmosphere (with a thickness of about 1000 g/cm^2), secondary particles are formed. The flux of these secondary particles at sea level is about 10^{-2} particle/(cm^2·sr·s) (70% are $\mu^{\pm}$ leptons, and 30% are $e^{\pm}$ leptons, i.e., electrons and positrons).[3]

Research on the primary cosmic rays is one of the central problems of cosmic-ray astrophysics. A colossal effort has already been devoted to its solution. This work is continuing on both high-altitude balloons and satellites. To characterize the scale of the largest installations, we might note that the space laboratory Spacelab 2, which was launched in July 1985 on the Space Shuttle, carried a University of Chicago package (The Egg) weighing about 2 metric tons, intended for studying nuclei with energies ranging from 50 GeV/nucleon to several TeV/nucleon. Results concerning the composition and spectrum of the cosmic rays have been reported at all of the International Cosmic Ray Conferences (ICRCs), including the present one. There have been both original papers and reviews.[6] Solely for illustration, we will present some figures here. Figure 1 shows[7] the energy spectra [this is the customary term for the differential efficiency $I_i(E)$, also called the "flux"] for H, He, C, and Fe nuclei. These spectra correspond to a period near the minimum of the solar cycle. The solid line for the hydrogen (H) spectrum corresponds to an extrapolation into interstellar space

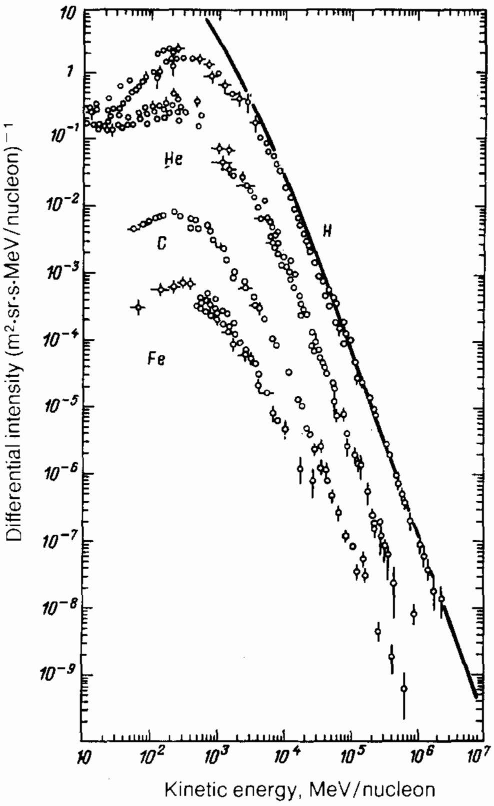

FIG. 1.

(i.e., beyond the boundary of the solar system), found by eliminating the modulation effect in the solar system. Just where the spectrum in interstellar space reaches a maximum is not known, so it may be necessary to increase the estimates in (1) by a factor of severalfold for the local galaxy (near the sun). Figure 2 shows[8] the elemental composition of the cosmic rays near the earth (the line corresponds to the cosmic rays, while the bars correspond to the chemical composition of the medium in the local galaxy near the solar system, according to astrophysical data). We note a circumstance which was established a long time ago (at the very beginning of research on the elemental composition of the cosmic rays, in the late 1940s): The cosmic rays include a fairly large number of nuclei which are rare in stars and in the interstellar medium. The most typical examples are Li, Be and B nuclei. Their abundance (relative to H) in the cosmic rays is about five orders of magnitude greater than that in the local galaxy. Another clear example is the isotope ^{3}He. In the cosmic rays, at $\mathscr{E}_k \approx 40$–150 MeV/nucleon, we have an intensity ratio $^3\mathrm{He}/^4\mathrm{He} \approx 7.5\cdot 10^{-2}$ (Ref. 9), while in nature we have $^3\mathrm{He}/^4\mathrm{He} \sim 10^{-7}$–$10^{-4}$, depending on the source (or sample). For the ratio of deuterium to hydrogen we have approximately the same value: $(^2\mathrm{H}/^1\mathrm{H})_{\mathrm{cr}} \approx 0.13$, in comparison with $(^2\mathrm{H}/^1\mathrm{H})_{\mathrm{nature}} \approx 1.5\cdot 10^{-2}$. The abundance in the cosmic rays of elements and isotopes which are rare in nature is explained on the basis that the cosmic rays which are arriving here have been wandering for a long time in the interstellar medium and, possibly, in their sources. Accordingly the heavier nuclei have had time to partially convert into lighter nuclei as a result of nuclear collisions. It follows from data on the elemental and isotopic compositions of the cosmic rays that the average amount of matter the cosmic rays have passed through is $x \sim 5$–10 g/cm^2. For relativistic nuclei, the velocity v can be assumed equal to the speed of light, c, and we can set $x = c\rho T$, where ρ is the density of the medium, and T is the time. For the interstellar medium, with a density $n \sim 1$ cm^{-3} ($\rho \sim 2\cdot 10^{-24}$ g/cm^3; it is mostly hydrogen), with $x \sim 5$ g/cm^2, the time would be[4] $T \sim 10^{14}$ s $\approx 3\cdot 10^6$ yr. An extremely important point is that the relative number of secondary nuclei falls off with increasing energy (unfortunately, data are available only for energies $\mathscr{E} \lesssim 100$ GeV/nucleon).

Heavy nuclei up to uranium have been observed in the cosmic rays. The relative number of heavy nuclei (which in fact are usually called "superheavy") in the cosmic rays is roughly the same as in the solar system (see Fig. 3, taken from Ref. 10). There have been reports in the literature of the detection of traces of nuclei with $Z \sim 110$ in meteoric matter, but to the best of our knowledge the presence of such nuclei in the cosmic rays cannot yet be regarded as an established fact.

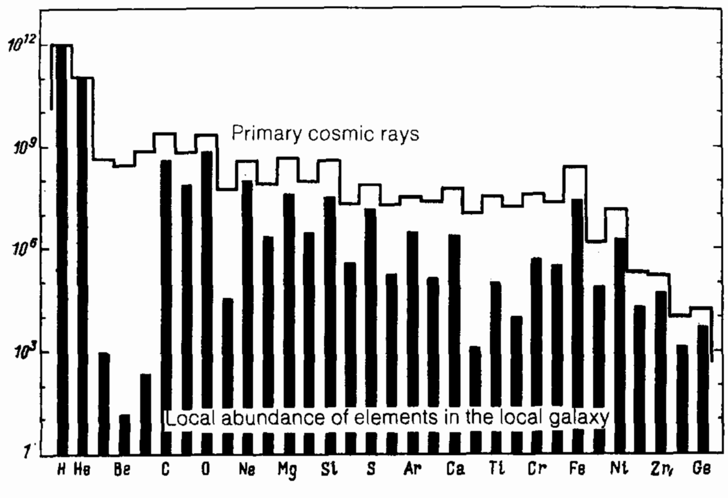

FIG. 2.

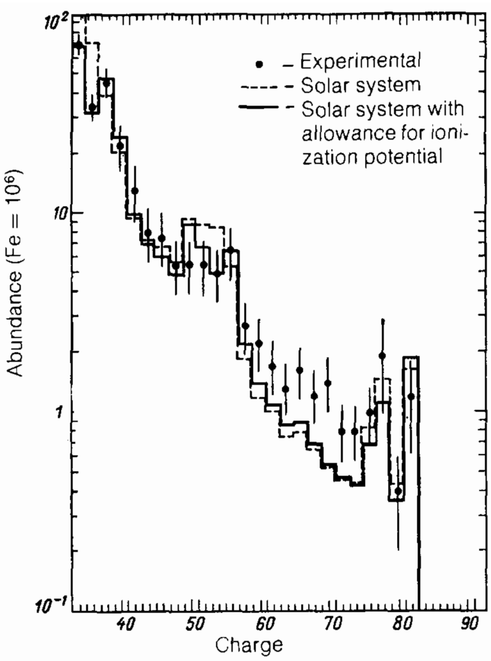

FIG. 3.

The electron component of the cosmic rays is usually studied without drawing a distinction between electrons (e^-) and positrons (e^+). At a given energy (say $E \sim 1$–3 GeV) the intensity of the electron component is of the order of 1% of the proton intensity. The energy density of the electrons is thus [see (1)]

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

The integral spectrum of electrons in the interval $5 < E < 100$ GeV is given approximately by

$$I_{\mathrm{e}}(>E) = 1.5\cdot 10^{-2}[E(\mathrm{GeV})^{-2}\ \mathrm{particle/(cm^2\cdot s\cdot sr)}. \qquad (3)$$

For all cosmic rays (at $10 < E < 3\cdot 10^6$ GeV), on the other hand, we have, very roughly,

$$I_{\mathrm{cr}}(>E) = [E(\mathrm{GeV})^{-1.7}\ \mathrm{particle/(cm^2\cdot s\cdot sr)}, \qquad (4)$$

and at $E > 3\cdot 10^6$ GeV we have

$$I_{\mathrm{cr}}(>E) = 3\cdot 10^{-10}[E(\mathrm{GeV})\cdot 10^{-6}]^{-2,1}\ \mathrm{particle/(cm^2\cdot s\cdot sr)}. \qquad (5)$$

The steepening (change in slope) of the cosmic-ray spectrum at $E \sim 10^6$ GeV is usually attributed to a relatively rapid escape of high-energy cosmic rays for the local galaxy.

Only in recent years have comprehensive and accurate data on the electron spectrum been obtained. These results are illustrated by Fig. 4 (Ref. 11), which shows the differential intensity multiplied by E^3, i.e., the quantity $E^3 I(E)$, expressed in units of particles per square meter per second per steradian $\times\mathrm{GeV}^2$. The exponent γ in the power-law differential spectrum $I(E) = KE^{-\gamma}$ evidently corresponds to the exponent $\gamma - 1$ in the integral spectrum $I(>E)$. Figure 4 thus generally agrees with spectrum (3), but at $E > 100$ GeV the electron spectrum steepens. The positron intensity I_{e}^{+} in the electron component at $E > 1$ GeV amounts to about 10% of the overall intensity $I_{\mathrm{e}^{-}+\mathrm{e}^{+}}$. Unfortunately, the data available are still rather inacccurate (Fig. 5; Ref. 11). Since 1979 we have begun to see data on antiprotons, $\bar{\mathrm{p}}$. At particle energies $E \sim 5$–10 GeV, we find a ratio $I_{\bar{\mathrm{p}}}/I_{\mathrm{p}} \sim 5\cdot 10^{-4}$ (see Ref. 12 and Fig. 6). At lower energies ($E_k \approx 130$–320 MeV), the measured intensity of antiprotons is significantly higher than that which one would expect under the natural assumption that they are produced as secondary particles as cosmic rays propagate through the interstellar medium (see the lower curve in Fig. 6). No antinuclei (heavier than $\bar{\mathrm{p}}$) have been seen in the cosmic rays.

The extent of the anisotropy of the cosmic rays was a matter of dispute for many years. Since this anisotropy is extremely slight, at least at $E < 10^5$ GeV, it is usually characterized by the first-harmonic amplitude, i.e., by the ratio $\delta = I_1/I_0$. The overall intensity is assumed to have an angular dependence $I = I_0 + I_1\cos\theta (I_1 \ll I_0$; the angle θ is reckoned from the direction of maximum intensity). At $E \lesssim 10^5$ GeV, the amplitude is $\delta \lesssim 10^{-3}$, and it increases with the energy (see Ref. 13 and Fig. 7; in this figure, λ is the latitude of the point at which the measurements were taken).

The field of research on cosmic rays with ultrahigh energies, $E \gtrsim 10^{17}$ eV, is a special one, in a sense.[5,13,14] The

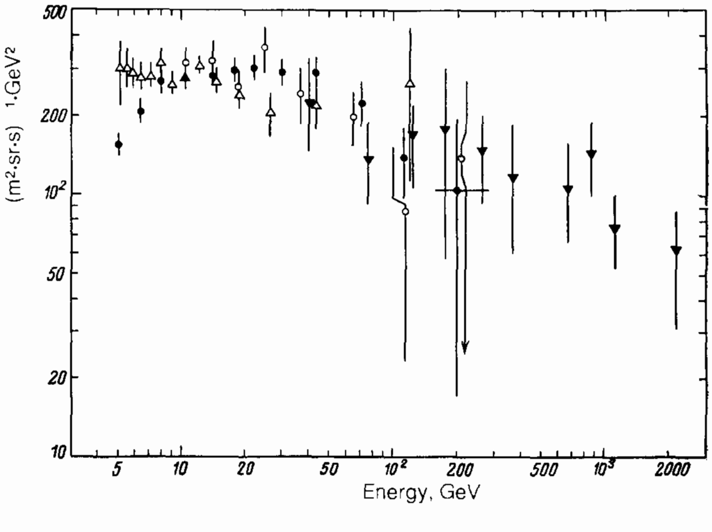

FIG. 4. The quantuity plotted along the ordinate axis is the differential intensity multiplied by E^3.

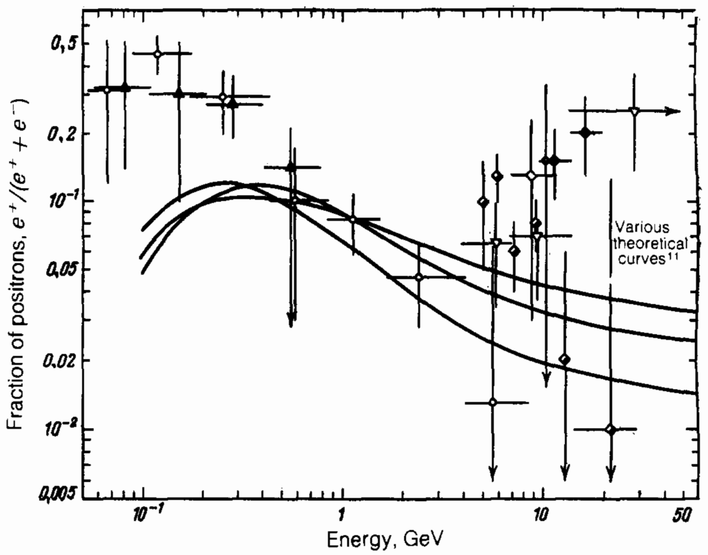

FIG. 5.

sources of data in this field are the extensive air showers which are observed at the earth's surface. Particles with energies ranging up to $E\sim 10^{20}$ eV and possibly even $E\sim 3\cdot 10^{20}$ eV are observed. The nature of the spectrum of all cosmic rays is clear from Fig. 8 [the quantity plotted along the ordinate axis is $E^{2.5}I(E)$; see Ref. 14]. The elemental composition in this region is known only poorly, and it is not clear whether this composition (especially at the very highest energies, $E\gtrsim 10^{19}$ eV) is the same as at lower energies. Also unclear is the question of a possible "cutoff" of the spectrum at $E\sim 3\cdot 10^{19}$ eV [such a cutoff would have to occur if the corresponding particles reach us from metagalactic distances as a result of the "stopping" of particles in collisions with photons of the background (relic) radiation with a temperature of 2.7 K].

We should stop here. The information presented here cannot replace a detailed review.[6–15] Our sole purpose has been to give an idea of the present state of affairs and to show how much has been accomplished as a result of many years of very difficult labor by a veritable army of "cosmic" physicists. It is clear that the picture is still far from complete, and our data on the primary cosmic rays near the earth need to be fleshed out substantially. This comment applies to literally everything, but especially to the elemental composition at high energies, the isotopic composition, the spectrum of positrons and antipositrons, and the cosmic rays of ultrahigh energies (the elemental composition, the spectrum, and the anisotropy).

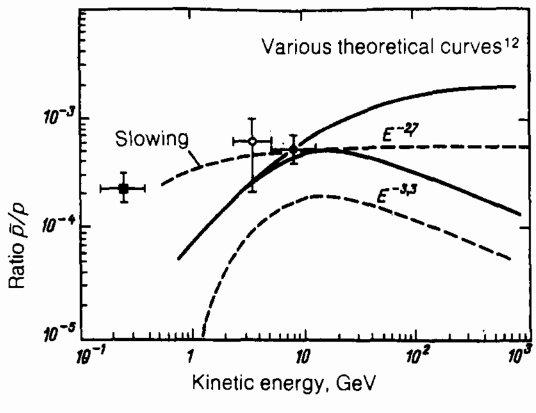

FIG. 6.

3. COSMIC RAYS IN THE UNIVERSE

Information on cosmic rays in the universe, far from the solar system, arrives here in many ranges of electromagnetic waves, but radio emission and γ emission are particularly important. The electron component of the cosmic rays is the primary source of nonthermal cosmic radio emission. The emission mechanism is the synchrotron mechanism; i.e., we are dealing with an emission by charges which are moving at relativistic velocities in a magnetic field. As we know, a particle of charge e and mass m in a uniform magnetic field **H** (we are talking about essentially a vacuum, so we will identify the magnetic field **H** with the magnetic induction **B**) moves along a helix. The orbital frequency is

$$\omega_H^* = \omega_H \frac{mc^2}{E} = \frac{|e|H}{mc}\frac{mc^2}{E} = 1.76\cdot 10^7 H\frac{mc^2}{E}\,\mathrm{s}^{-1}, \tag{6}$$

where the particle is assumed to be an electron (or positron), and the field is expressed in oersteds in the conversion to the numerical factor. An ultrarelativistic particle ($E\gg mc^2$) moving at a velocity **v** makes an angle $\chi\gg mc^2/E$ with the field **H** and radiates waves with many frequencies which are multiples of $\omega_H^*/\sin^2\chi$. The spectrum is essentially continuous, and for an individual electron the radiation intensity reaches a maximum at the following frequency ($H_\perp = H\sin\chi$ is the field component perpendicular to the velocity **v**):

$$\nu_m = \frac{\omega_m}{2\pi} = 0.07\frac{|e|H_\perp}{mc}\left(\frac{E}{mc^2}\right)^2 = 4.6\cdot 10^{-6}H_\perp[E(\mathrm{eV})]^2\ \mathrm{Hz}. \tag{7}$$

In a typical interstellar field $H\sim 10^{-6}$–10^{-5} Oe, for electrons with $E\sim 10^9$ eV, the frequency would be $\nu_m\approx 1.5\cdot 10^7$

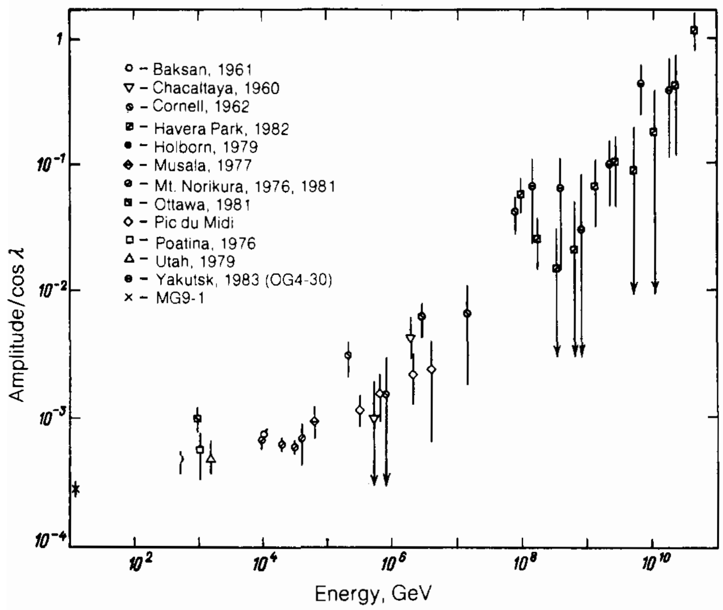

FIG. 7.

Hz (and the wavelength $\lambda = \frac{c}{\nu_m} \approx 2$ m; for definiteness, we have set $H_\perp \approx 3\cdot 10^{-6}$ Oe). The electron component of the cosmic rays in interstellar space thus emits in specifically the ratio range. In regions with a strong magnetic field and/or for electrons with high energies, the synchrotron radiation may of course fall in the optical, x-ray, or even γ-ray range. In the Crab Nebula, for example, with $H \sim 10^{-3}$ Oe and $E \sim 10^{13}$ eV (the electrons are injected by the pulsar PSR 0531), according to (7), we would have $\nu_m \sim 5\cdot 10^{17}$ Hz and $\lambda_m \sim 10$ Å. The optical and x radiation from the Crab with a continuous spectrum is indeed of a synchrotron nature, as can be seen particularly clearly from the high degree of polarization of the radiation (a high degree of polarization is characteristic of specifically synchrotron radiation; the electric field in the waves is at a maximum in the direction perpendicular to the projection of the magnetic field onto the visual plane). In pulsars, for fields $H \sim 10^{12}$ Oe, curvature radiation, which is related to synchrotron radiation, is particularly effective. We do not have space here, of course, to go into a detailed discussion of the theory of synchrotron radiation.[4,5,16] It is sufficient to note that the intensity of this radiation along the line of sight for monoenergetic electrons at the frequency ν_m [see (7)] is

$$J_{\nu,\mathrm{m}} = 1.7\cdot 10^{-23} H_\perp \tilde{N}_\mathrm{e}\ \mathrm{erg/(cm^2\cdot s\cdot sr\cdot Hz)}, \tag{8}$$

where $\tilde{N}_\mathrm{e} = \int N_\mathrm{e}(r)\mathrm{d}r = N_\mathrm{e}L$ is the total number of isotropically distributed radiating electrons along the line of sight (N_e is their average density, and L is the size of the radiating region). For electrons with an isotropic directional distribution and a power-law spectrum $N_\mathrm{e}(E)\mathrm{d}E = KE^{\;\gamma_\mathrm{e}}\mathrm{d}E$, the intensity is

$$J_\nu = 1.35\cdot 10^{-22} a(\gamma_\mathrm{e}) LK_\mathrm{e}H^{(\gamma_\mathrm{e}+1)/2} \times \left(\frac{6.26\cdot 10^{18}}{\nu}\right)^{(\gamma_\mathrm{e}-1)/2} \mathrm{erg/(cm^2\cdot sr\cdot s\cdot Hz)} \tag{9}$$

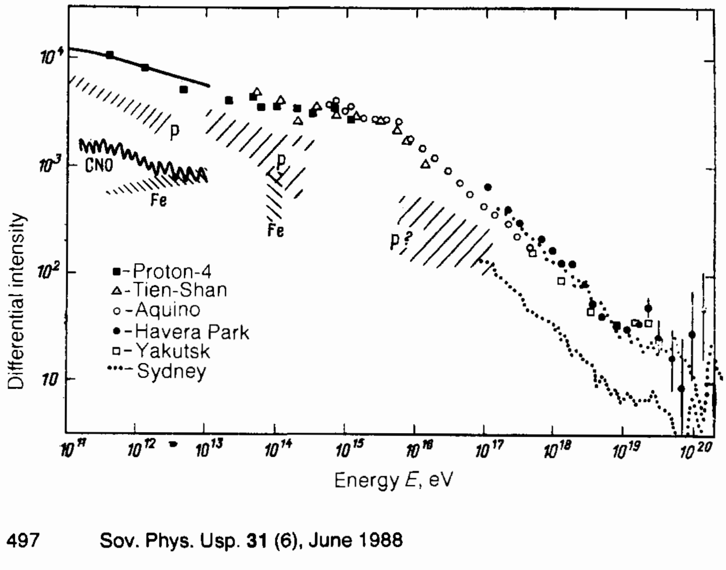

FIG. 8. The units for the ordinate scale are particles per square meter per second per steradian times GeV$^{1.5}$.

[for the ordinary values $\gamma_e \sim 1.5$–5, the coefficient here is $a(\gamma_e \sim 0.1$, and the values of K_e and $H^{(\gamma_e+1)/2}$ are certain averages along the line of sight; the field **H** is assumed here to be isotropic on the average].

The radio-emission spectrum is thus also a power-law spectrum:

$$J_\nu \propto \nu^{-\alpha}, \quad \alpha = \frac{1}{2}(\gamma_e - 1). \tag{10}$$

It is clear from (8) and (9) and from the very essence of the matter that by measuring the intensity of the radio emission, J_ν, one can find the density of electrons along the line of sight (from measurements of, say α, we find γ_e, and the intensity J_ν itself can be used to find the product LK_e).

In this case, however, it is necessary to determine the field **H** on the basis of independent considerations. There are several ways to do this.[5] We will discuss one of these methods here; although indirect, it is of major importance in cosmic-ray astrophysics. In magnetohydrodynamics and plasma physics, for quasisteady conditions, a rough equality of the energy density of the cosmic rays and the energy density of the magnetic field seem natural on the basis of both theoretical considerations and experimental data:

$$w_{\text{cr}} \sim w_H = \frac{H^2}{8\pi}. \tag{11}$$

In the more general case we can set $w_H = \varkappa_H w_{\text{cr}}$. Unfortunately, we do not know the density w_{cr} from the radio data, and unless we appeal to some other data (primarily from γ-ray astronomy; more on this below), we are forced to work on the basis of the relationship between the densities $w_{\text{cr,e}}$ and $w_{\text{cr}} = \varkappa_e w_{\text{cr,e}}$. Near the earth we have $\varkappa_e \sim 10^2$ [see (1), (2)]. If we are given values of $\varkappa_H$ and $\varkappa_e$, then we can find w_{cr}, $w_{\text{cr,e}}$, and $H^2/8\pi$ from the radio data [or, more precisely, we can find their average values along the line of sight; for discrete sources, e.g., a supernova envelope, we could use the same method to determine energies integrated over the volume, W_{cr}, $W_{\text{cr,e}}$, and $W_H = \int (H^2/8\pi)\mathrm{d}V$]. Information on cosmic rays in the local galaxy, supernova envelopes, radio galaxies, etc., was obtained by this approach 30 years ago (see Ref. 4 and the bibliography there), under the assumption $\varkappa_H \sim 1$ and $\varkappa_e \sim 10^2$.

The general conclusions are now well known.

Cosmic rays are a universal phenomenon, present in the plasma in space not as an exception but as a rule. This result is completely understandable, since there is a long list of instabilities and processes which could occur in a plasma, including motions of inhomogeneities and shock waves. As a result, particles of all species would be accelerated. The relativistic tails on the energy distributions of these particles would constitute cosmic rays. Generally speaking, the acceleration proceeds until the inverse effect of the accelerated particles on the nonrelativistic plasma in space, with the frozen-in magnetic fields, begins to have a strong effect. A roughly equal distribution of energy between cosmic rays and the magnetic field [see (11)] is thus quite natural. The internal-energy density of the interstellar gas is frequently also of the same order of magnitude as w_{cr} and w_H. In regions with a density $n \sim 1$ cm^{-3} and $T \sim 10^4$ K, for example, the energy density is $w_g = (3/2)k_B nT \sim 10^{-12}$ erg/cm^3, i.e., the same as the density w_{cr} near the earth [see (1)] and in general in the galactic disk.

In intense radio galaxies, the cosmic-ray energy W_{cr} estimated in this manner reaches 10^{60} erg or even 10^{61} erg $\sim 10^7 M_\odot c^2$. Our galaxy is "normal." Its gaseous disk has a thickness $2h_g \sim 200 n_g \sim 6 \cdot 10^{20}$ cm, and its radius is $R \sim 5 \cdot 10^{22}$ cm. In such a volume, $V \sim 5 \cdot 10^{66}$ cm^3, the total energy of the cosmic rays would be $W_{\text{cr}} \sim w_{\text{cr}} V \sim 5 \cdot 10^{54}$ erg $\sim 3 M_\odot c^2$. There is no doubt, however, that cosmic rays occupy a much larger region, since they do go beyond the disk. At a minimum we are talking about a radio disk with a thickness $2h_r \sim 5 \cdot 10^{21}$ cm. At least since 1953, however, several authors, including the present author,[17] have believed that the local galaxy has a fairly well-defined radio halo (which of course might also be called a "thick radio disk," especially if it is flattened). The volume of a quasispherical halo is $V_h \sim \frac{4\pi}{3} R^3 \sim 5 \cdot 10^{68}$ cm^3, and even when we allow for the decrease in the density w_{cr} with distance from the galactic plane we find $W_{\text{crG}} \sim 10^{56}$ erg in the local galaxy. The halo problem has been the subject of extensive debate, since its characteristics are difficult to determine through observations from the earth. I went into this question in some detail 10 years ago in a report to the 15th ICRC (see Ref. 6 and also 18). At the time, "edge-on" observations of the galaxies NGC 4631 and NGC 891 were the latest news. Figure 9 shows radioisophotes of the galaxy NGC 4631 at the wavelength $\lambda = 49.2$ cm ($\nu = 610$ MHz) (the white area is the image of the galaxy in visible light; this figure was graciously furnished by R. Sansisi). That the radio halo is considerably larger than the optical image is obvious. Unfortunately, the recent progress in research on galactic halos has not been particularly noteworthy. One reason, in my opinion, is the absence of state-of-the-art radiotelescopes with a sufficiently high angular resolution for operation at wavelengths longer than 1 m. The longer the wave, the larger the radio halo should be, since the energy of the electrons and the magnetic field generally decreases with distance from the galactic plane (so progressively longer waves will obviously be radiated). We should stress here that in addition to radio halos[4,5] we could speak in terms of a gaseous halo, a magnetic halo,[19] or a cosmic-ray halo.[5] In the latter case, the meaning would be the corresponding region occupied by cosmic rays. In this region, especially at its periph-

FIG. 9.

TABLE II. γ astronomy

γ radiation with a continuous spectrum	Sources and emission mechanisms
$E_\gamma < 30$–50 MeV (balloons and satellites)	Diffuse background (galactic and metagalactic)
$E_\gamma > 30$–50 MeV and up to several GeV (balloons and satellites)	Discrete sources (pulsars, quasars, molecular clouds, Cyg X-3)
$E_\gamma > 10^{11}$–10^{12} eV (Cherenkov radiation in the atmosphere)	Emission mechanisms (bremsstrahlung, synchrotron radiation, curvature radiation, Compton scattering, $\pi^0 \to \gamma + \gamma$, etc.)
$E_\gamma > 10^{14}$ eV and up to 10^{16} eV (extensive air showers)	
γ lines:	
γ lines of nuclei, $E_\gamma \sim 1$–10 MeV (lines from nuclei at rest; "bands" from cosmic-ray nuclei)	
The annihilation $e^+ + e^- \to \gamma + \gamma$, $E_\gamma = 0.511$ MeV	
Cyclotron radiation in very strong magnetic fields $[\omega_{H}^{*} = (eH/mc)mc^2/E$; at $H = 10^{13}$ Oe, $\hbar\omega_{H}^{*} \sim 0.1$ MeV$]$	
γ bursts (first publications in 1973)	
Sources: probably neutron stars. Nature?	

ery, there may be few electrons of fairly high energy (because of the energy loss), and the magnetic field may be greatly weakened. The radio halo may thus be imperceptible, while the average density $w_{\rm cr}$ will still be significant.

The radio-astronomy data indicate that the radio halos of different galaxies, even of similar type, may be either bright or faint. From this standpoint, the example of the galaxies NGC 4631 and NGC 891, with well-defined radio halos, cannot yet be regarded as proof that the local galaxy has a radio halo (see p. 208 in Ref. 15). However, an analysis of the radio emission from the local galaxy also leads to the conclusion that it does have a radio halo, with a dimension $R \sim 10$ kpc (see Ref. 5 and the bibliography there).

If radio astronomy has not furnished cosmic-ray astrophysics a wealth of important new data over the past decade, γ-ray astronomy has contributed some important and sometimes unexpected results. It would have been pleasant to have learned more, of course, but the prolonged absence of γ-ray satellites, which we have already mentioned, has interfered. Although young, γ-ray astronomy has already managed to branch out quite extensively (Table II). Continous-spectrum γ radiation is produced by both the electron and proton-nuclear components of the cosmic rays. The role played by the proton component is particularly interesting since relativistic electrons can be and are being studied by means of their emission in the rf, optical, and x-ray ranges. Protons may also contribute something to the emission in these ranges, but that component is usually insignificant or totally absent [in a field $H \approx 10^{-5}$ Oe, for example, the synchrotron radiation of protons with an energy $E \lesssim 10^{-12}$ eV occurs at a frequency $\nu_m \lesssim 10^4$ Hz; see (7) with $m = M_{\rm p}$]. The protons and nuclei which are part of the cosmic rays produce π^0 mesons in collisions with nuclei in a gas; these mesons decay very rapidly (the average lifetime of a π^0 is $0.84 \cdot 10^{-16}$ s), in a process accompanied by the production of γ rays. The decay of a π^0 meson occurs with a probability of 98.8% by the mechanism $\pi^0 \to 2\gamma$, so γ rays with an energy $E_\gamma = (1/2) m_{\pi^0} c^2 = 67.5$ eV are produced in the decay of a π^0 meson at rest. Other reactions and decays (e.g., the decay $\Sigma^0 \to \Lambda + \gamma$) play a much small role, and for brevity we will discuss only the production and decay of π^0 mesons. The intensity of the γ rays produced in this manner is naturally proportional to the density of nuclei in the gas, n, and to the cosmic-ray intensity $I_{\rm cr}$. The differential intensity in the number of γ rays (the γ-ray spectrum) along the line of emission (the coordinate r) is given by

$$I_\gamma (E_\gamma) = \int \sigma (E_\gamma, E)\, n(r)\, I_{\rm cr}(r, E)\, {\rm d}E\, {\rm d}r, \qquad (12)$$

where $\sigma(E_\gamma, E)$ is the corresponding effective cross section for the production of cosmic rays with an energy E by γ rays with an energy E_γ (this cross section must of course be averaged to take account of the elemental and isotopic composition of the cosmic rays and nuclei in the gas). For the flux of γ rays from a discrete source we find from (12)

$$F_\gamma (> E_\gamma) = \int_\Omega I_\gamma (> E_\gamma)\, {\rm d}\Omega \approx \frac{\overline{(\sigma I_{\rm cr})}\, \tilde{n}(V)}{R^2}, \qquad (13)$$

where Ω is the solid angle subtended by the source, $\overline{(\sigma I_{\rm cr})}$ is the cross section averaged over the cosmic-ray spectrum [see (12)], and $\tilde{n}$ is the number of gas nuclei in a source of volume V at a distance R (see Refs. 5 and 16, for example, for more details). It is clear from this discussion [see (12) and (13)] that the emision of γ rays in the decay of π^0 mesons would make it possible to find the intensity of cosmic rays (of their proton-nuclear component) far from the earth. It is of course necessary to know the amount of gas (primarily atomic and molecular hydrogen) in the corresponding regions [the factors n and $\tilde{n}$ in (12) and (13)], but it is specifically the density of the interstellar gas (more precisely, the density of atomic hydrogen) which can be found quite well by the radio-astronomy method (on the basis of the line at $\lambda = 21$ cm for hydrogen atoms).

This possibility of directly studying the basic (proton-nuclear) component of the cosmic rays in the universe is the reason for the extremely important role played by γ-ray astronomy in cosmic-ray astrophysics. In other words, γ-ray astronomy occupies the same position with regard to research on the proton-nuclear component as radio astronomy occupies with regard to the electron component. In particular, the γ-astronomy method would in principle make it possible—through the reception of γ radiation from the Magellanic Clouds[20] and a determination of the gradient of the cosmic-ray intensity in the direction of, say, the anticenter of the local galaxy[21]—to obtain information about cosmic rays in the metagalaxy (more specifically, here we have a method for testing metagalactic models of the origin of the cosmic rays in the local galaxy; more on this below).

Unfortunately, as we have already noted, γ-ray astronomy is developing more slowly than one might wish and more slowly than would be quite possible in principle. This comment applies particularly well to research on the γ rays from the decay of π^0 mesons generated by the bulk of the proton-nuclear component of the cosmic rays. Today, all our hopes are pinned on the Soviet Gamma γ-ray observatory and the American GRO, which are scheduled for launching in the near future (there is the hope that the Gamma will be launched in 1988). The basic telescope of the Gamma observatory, the Gamma-1, with a mass of 1500 kg, is to detect γ radiation in the range 50–5000 MeV. Its angular resolution will be 2° or, with a special "mask," 17′. The minimum detectable flux will be $F_\gamma \sim 5\cdot 10^{-8}$ photon/(cm$^2\cdot$s). In the future we need to keep a γ observatory in orbit at all times, and it would be preferable to have several, rather than only one. We also need a multifaceted "patrol" for studying supernova explosions,[22] so as to avoid repeating the history of events associated with supernova 1987A in the Large Magellanic Cloud. We furthermore must not ignore the possibilities of γ-ray astronomy on high-altitude balloons [for example, we might cite the study of Von Ballmoos *et al.*[23] of γ rays from the radiogalaxy Centaurus A (Cen A) in the range 0.7–20 MeV].

I would like to go back to what has already been done, since it is certainly not my intention to depreciate the achievements of the satellite SAS II or, especially, COS-B. As an example, Fig. 10 shows some of the COS-B results[24] for γ rays with energies E_γ from 70 MeV to 5 GeV (Fig. 10a shows an intensity map, in the galactic longitude and the band of galactic latitudes $|b| \leqslant 20°$; Fig. 10b shows the longitudinal distribution of the intensity; here an average has been taken over the latitude band $|b| < 5°$). Unfortunately, the cosmic-ray gradient in the local galaxy has not yet been reliably established, and this point is a matter of some dispute (see Refs. 25, the most recent papers of which we are aware, which contain some corresponding bibliographies). It is important to note that the observations do not contradict the suggestion that the energy density of cosmic rays falls off toward the anticenter (and in general, along the radius reckoned from the galactic center) in accordance with a law $w_{\rm cr} \sim e^{-r/R}$, where $R \sim 10$–15 kpc (a distance of 10 kpc was selected as the distance from the center to the sun; today, a distance of 8 kpc is accepted). This conclusion (provided, of course, that the gradient is real, and this reality still has to be proved, strictly speaking) is in complete accordance with a galactic model with a halo. The cosmic-ray halo should have a typical dimension $R \sim 15$ kpc. We will have more to say about this subject in the following section of this paper.

About 20 discrete γ sources were detected on COS-B [at a sensitivity $F_\gamma > 10^{-6}$ photon/(cm$^2\cdot$s)]. Among these sources are the pulsars PSR 0531 (Crab) and PSR 0833 (Vela), the quasar 3C273, and the hydrogen cloud (molecular cloud) ρ-Ophiuchi. The other sources have still not been indentified; among them is Geminga ($\equiv$2 CG 195 + 04), which is one of the most intense sources in the γ range. [The flux from it is $F_\gamma(>E_\gamma = 100\ \text{MeV}) = 4.0\cdot 10^{-6}$ photon/(cm$^2\cdot$s)]. It is quite probable that some of the unidentified sources are molecular clouds or pulsars. In addition to the γ sources which were studied by COS-B, we might also mention the radio galaxy Cen-A, the Seyfert galaxy NGC 4151, and the galactic x-ray source Cyg X-3 (Cygnus X-3). The typical luminosity of the galactic γ sources is $L_\gamma \sim 10^{34}$–10^{36} erg/s [for the spectrum $F_\gamma(E_\gamma) = K_\gamma E_\gamma^{-3}$, for example, under the assumption of an isotropic emission, the luminosity would be

$$L_\gamma = 4\pi R^2 \int E_\gamma F_\gamma \,\mathrm{d}E_\gamma = \frac{4\pi R^2 K_\gamma}{E_\gamma};$$

if $F_\gamma(>F_\gamma = 100\ \text{MeV}) = 1/2K_\gamma E_\gamma^{-2} \sim 5\cdot 10^{-6}$ photon/(cm$^2\cdot$s), then at a distance of 1000 pc $\approx 3\cdot 10^{21}$ cm we would have $L_\gamma \sim 10^{35}$ erg/s]. For the pulsar PSR 0531 (Crab) we have $L_\gamma(50\ \text{MeV} < E_\gamma < 10\ \text{GeV}) = 2\cdot 10^{35}$ erg/s. The total γ luminosity of the local galaxy is $L_\gamma(>E_\gamma = 70\ \text{MeV}) \sim 10^{39}$ erg/s, which corresponds to about $2\cdot 10^{42}$ photon/s with the observed spectrum. Incidentally, the total luminosity of the local galaxy in the radio range is $L_{\rm r} \sim 3\cdot 10^{38}$ erg/s.

For the quasar 3C273 we have $L_\gamma(50 < E_\gamma < 500\ \text{MeV}) = 2\cdot 10^{46}$ erg/s (a distance of 790 Mpc has been assumed, with a redshift $z = 0.158$). The total luminosity of the quasar apparently does not exceed $L = (2$–$5)\cdot 10^{47}$ erg/s, while its x-ray luminosity is $L_{\rm X}(>E_{\rm X} > 4.5\ \text{keV} = 1.7\cdot 10^{46}$ erg/s.

Perhaps particularly striking is the very high γ luminosity at energies $E_\gamma > (1$–$5)\cdot 10^{11}$ eV [ground-based observations of (Vavilov-) Cherenkov radiation in the atmosphere] and at $E_\gamma > 10^{14}$ eV (ground-based observations of extensive air showers). The object which has attracted the most attention in these regions is the source Cyg X-3, which is possibly a young pulsar in a binary system with an orbital period of 4.8 h (Ref. 26). For Cyg X-3, the luminosities are $L_\gamma(>E_\gamma = 40\ \text{MeV}) \approx 3\cdot 10^{38}$ erg/s, $L_\gamma(>E_\gamma = 2\cdot 10^{12}) \approx 5\cdot 10^{36}$ erg/s, and $L_\gamma(>\text{E}_\gamma = 2\cdot 10^{15}\ \text{eV}) \approx 1\cdot 10^{36}$ erg/s [according to some other estimates, based on the assumption that the distance to Cyg X-3 is $R \approx 13$ kpc, we would have a luminosity $L_\gamma(>E_\gamma = 10^{12}\ \text{eV}) \approx (2$–$5)\cdot 10^{37}$ erg/s, and in the interval $3\cdot 10^{15} < E_\gamma < 10^{16}$ eV the luminosity would be $L_\gamma \approx 3\cdot 10^{36}$ erg/s; the emission has been assumed to be isotropic, as in the other cases]. For the source Vela X-1, the estimate $L_\gamma(>E_\gamma = 3\cdot 10^{15}\ \text{eV}) \approx 2\cdot 10^{34}$ erg/s has been of-

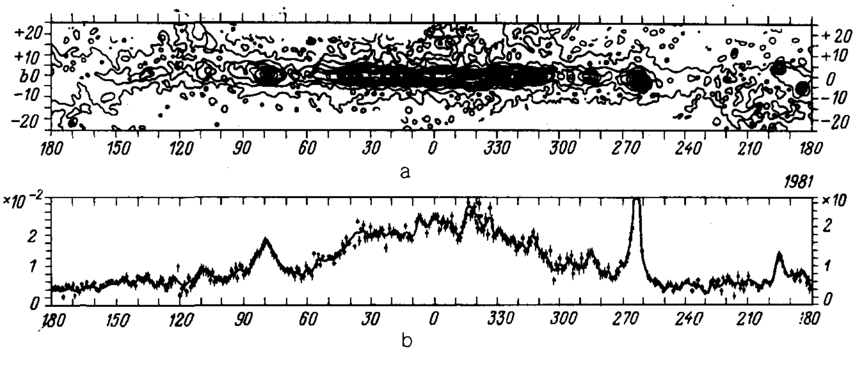

FIG. 10.

fered. It is true that the luminosity is reduced by a factor of $4\pi/\Omega$ if the γ radiation is directional and is concentrated in a solid angle Ω. Such intense γ emission could probably be generated only by protons. For the strength (luminosity) of protons in the case of Cyg X-3 we find estimates of the magnitude $L_p(>E_p = 10^9\ \text{eV}) \sim 10^{40}$ erg/s and $L_p(10^{16} < E_p < 10^{17}\ \text{eV}) \sim 10^{39}$ erg/s (here, and everywhere else in this report, we are not striving for high accuracy, and we are furthermore not stipulating all the assumptions which were made in the estimates; see also the Supplement).

Unfortunately, we cannot go further into detail on γ astronomy and its relationship with cosmic rays here. it is hoped, however, that even the rather fragmentary comments which we have offered here clearly show just how powerful and promising the γ-astronomy method is for studying cosmic rays in the universe. This fact is of course reflected in the program of this conference: About 130 reports, i.e., about 15% of the total, are devoted to γ-ray astronomy.

4. ORIGIN OF COSMIC RAYS; GALACTIC MODEL WITH A HALO

The "problem of the origin of cosmic rays" is customarily understood as the complex of questions concerning the origin of the primary cosmic rays near the earth and, in general, in the solar system. One could of course also speak of the origin of cosmic rays in, say, radio galaxies. It is obvious, however, that cosmic rays near the earth are a special topic since it is only about these cosmic rays that we have a wealth of "direct" data. We will thus be interested here only in the origin of the cosmic rays which reach the earth.

In order to solve the problem it is necessary to specify the "capture region": the region from which the cosmic rays arrive—where they undergo their random walk. It is necessary to specify the sources of the cosmic rays, the mechanisms by which they are accelerated, and the nature of their propagation in interstellar space. The set of all this information and its interpretation constitutes the theory of the origin of the cosmic rays. A key question is the choice of a model. In order to make this choice it is first necessary to select the capture region that we just mentioned. On occasion there has been a discussion of, for example, a solar model: The cosmic rays which arrive here (and, without any further stipulation, we will be talking exclusively about these cosmic rays) are assumed to be accelerated at the sun and captured in some circumsolar region (with a size $R \sim 10^{16}$–10^{18} cm, say). Today, on the other hand, we known that cosmic rays in roughly the same number occupy at least part of the galactic disk, and most of them arrive here from the local galaxy. Solar cosmic rays are of interest and are being studied widely, but that is a separate matter.[6] The point of pertinence here is, of course, that there is no need to examine a solar model for the origin of the cosmic rays (in the sense stated above). Representing another "extreme" are the metagalactic models of the origin of the cosmic rays. It is assumed in these models that for the most part the cosmic rays enter the local galaxy from outside it: from metagalactic space. Metagalactic models came under criticism a long time ago (see, in particular, Refs. 4 and 17). After the 1965 discovery of the thermal background (relic) radiation with a temperature $T \approx 2.7$ K, it became obvious that the electron component of the cosmic rays could not be of metagalactic origin and must be generated in the local galaxy itself. The reason is that the loss which results from scattering (the so-called inverse Compton effect) of electrons by thermal photons is so intense that electrons with an energy $E > 10^9$–10^{10} eV—the electrons which are responsible for a large part of the synchrotron galactic radio emission—could not reach us even from the radio galaxy nearest us, Centaurus A. It is also likely that the heaviest nuclei would also be unable to reach us from the metagalaxy, because of nuclear losses. With regard to protons and light nuclei, we do not yet have an equivalently direct and unambiguous way to refute the metagalactic models. It appears that only γ-astronomy observations—studies of the Magellanic Clouds[20] and of the gradient in w_{cr} in the local galaxy[21,25,27–29]—are capable of giving us a completely clear picture. In our opinion, however, the set of all the data presently available is a sufficient basis for rejecting the metagalactic models (this comment does not apply to the particles with the highest energies, $E > 10^{17}$ eV, or, more precisely, even with $E \gtrsim 10^{19}$ eV, which are apparently of metagalactic origin[13,14]).

We are thus left with the galactic models. In the galactic models, the cosmic rays (observed at the earth) are generated in the local galaxy and are captured in it, although most of them flow out into metagalactic space. Galactic models can be classified as disk models and halo models. In the disk models, the cosmic rays are concentrated in a certain disk which, although thicker than the gaseous disk of the galaxy (for which the half-thickness is $h_g \sim 100$ pc) is nevertheless quite flat, having, say, the half-thickness of the radio disk, $h_r \sim 500$–1000 pc (Fig. 11). In the halo models it is assumed that there exists a halo (or corona) of cosmic rays with a characteristic size $R \sim h_h \sim 10$–15 kpc. On the basis of physical considerations (think how difficult it would be to confine relativistic particles to the disk) and the radio data (which, admittedly, were unconvincing at the time), I was an adherent of the halo models from the very outset (since 1953; Ref. 17) (this point was already mentioned back in §3). It seem to me that all the data either confirm this model or, at worst, fail to contradict it. The fact that the size of the cosmic-ray halo has not yet been established is another matter. Furthermore, a halo of cosmic rays is sometimes identified with the ratio halo, but this identification is of course incorrect (see §3 above). In this connection, some purely semantic disagreements have arisen (e.g., a flattened radio halo with a half-thickness $h_h \sim 3$ kpc might be call a "thick disk").

The γ-astronomy data which provide evidence that the energy-density gradient w_{cr} is small refute the metagalactic models, although not totally, at the low accuracy which prevails today. In any case, if we are talking about galactic mod-

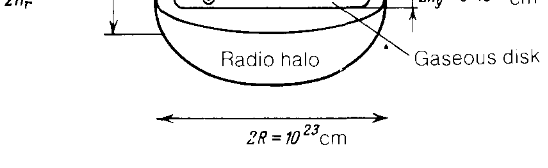

FIG. 11. ($2h_r \sim 5\cdot10^{21}$ cm)

els then a small gradient is compatible with only a large halo.[28] Incidentally, while an attempt has been made[27] to revive somehow the possibility of using a metagalactic model, a more careful analysis of the data from the same satellite, COS-B, makes a metagalactic model look unlikely. Actually, there are several other considerations which would make such a model unlikely (see Refs. 4 and 5 and the bibliography there).[6]

We will thus discuss a galactic model with a halo. The typical parameter values of this model (we are talking only order-of-magnitude) are listed in Table III.

The typical lifetime of the cosmic rays, T_{cr}, can be estimated on the basis of a variety of considerations. The simplest approach is based on an expression for the thickness of matter traversed, $x = c = \rho T_{\text{cr}}$ (see above), which is found from data on the chemical composition of the cosmic rays. For the interstellar medium we would have $\rho \sim 2 \times 10^{-24} n$ g·cm^3, where n is the density of the gas. For the local galaxy as a whole, and allowing for the presence of cosmic rays in the halo, we would have, crudely, $n \sim 10^{-2}$ cm^{-3} and $T_{\text{cr}} \sim 10^{16}$ s $\sim 3 \cdot 10^8$ yr (at $x \approx 5$–7 g·cm^3). Since the value adopted for n is unrealiable (we know the gas density in the halo only poorly), some more-detailed calculations based on an analysis of the propagation of cosmic rays in the local galaxy are slightly more convincing.[7] Their sources are concentrated in the disk, but they undergo their random walk not exclusively within the disk, moving out into the halo, returning to the disk, and so forth. The motion of cosmic rays in interstellar fields is of course not identical to the diffusion of neutral atoms in some inhomogeneous medium. For a fairly long list of reasons, however, the diffusion approximation is widely used, with justification, in analyzing the propagation of cosmic rays. Unfortunately, we do not have room here to discuss all these many questions. We will content ourselves with citing some reviews[4,5,16,30] which in turn cite large numbers of other reviews and original papers. As an example, we write a fairly general diffusion equation for the density of particles of species i [$N_i(\mathbf{r},t,E)\,\mathrm{d}\mathbf{r}\mathrm{d}E$ is the number of particles in the volume-energy element $\mathrm{d}\mathbf{r}\mathrm{d}E$]:

$$\frac{\partial N_i}{\partial t} - \operatorname{div}(D_i \nabla N_i) + \frac{\partial}{\partial E}(b_i N_i) = Q_i - P_i N_i + \mathcal{P}_i. \tag{14}$$

In an even more general case, the diffusion coefficient $D_i(\mathbf{r},t,E)$ could be regarded as anisotropic; the coefficient $b_i(\mathbf{r},t,E)$ determines the energy loss; Q_i represents "external" sources of cosmic rays of species i; the term $-P_iN_i$ incorporates "catastrophic" processes which result in the escape of particles of species i from the element $\mathrm{d}\mathbf{r}\mathrm{d}E$ under consideration; and, finally, the term $\mathcal{P}_i$ incorporates the influx of particles into this element, again as a result of catastrophic losses of particles of other species. For nuclei, the role of this catastrophic loss would be played by collisions with gas nuclei (density n) accompanied by a conversion into other nuclei or a substantial change in energy; i.e., we would have $P_i = \sigma_i v_i n$(σ_i is the corresponding average cross section, and v_i is the velocity of a nucleus of species i). The continuous losses for nuclei consist primarily of ionization losses, which are extremely small in the relativistic region for the interstellar medium. The assumption $b_i = 0$ is thus ordinally made for relativistic nuclei in (14). Other simplifications are frequently possible, but even with them equations of the type in (14) are extremely rich in content.[8]

TABLE III. Galactic model with a halo.

Dimensions of cosmic-ray halo, $R \sim 10$–15 kpc ~ 3–$5 \cdot 10^{22}$ cm (the radio halo is slightly smaller; its dimensions depend on the frequency, increasing with decreasing frequency)
Volume $V_{\text{h}} \sim 10^{68}$ cm^3
Total cosmic-ray energy $W_{\text{cr}} \sim w_{\text{cr}} V_{\text{h}} \sim 10^{56}$ erg $\sim 100\, M_{\odot} c^2$
Total energy of electrons $W_{\text{cr,e}} \sim w_{\text{cr,e}} V_{\text{h}} \sim 10^{54}$ erg
Typical cosmic-ray lifetime $T_{\text{cr}} \sim (1$–$3) \cdot 10^8$ yr $\sim (3$–$10) \cdot 10^{15}$ s (protons, light nuclei)
Luminosity of cosmic-ray sources $U_{\text{cr}} \equiv L_{\text{cr}} \sim W_{\text{cr}}/T_{\text{cr}} \sim (1$–$3) \times 10^{40}$ erg/s
Luminosity of electron sources $U_{\text{cr,e}} \sim W_{\text{cr,e}}/T_{\text{cr,e}} \sim 10^{39}$ erg/s

In the simplest diffusion approximation one introduces a constant diffusion coefficient $D_i = D$, and if the cosmic-ray lifetime T_{cr} is determined by escape from the system (from the halo), then one has $T_{\text{cr}} \sim R^2/2D$. With $R \sim 3 \cdot 10^{22}$ cm, a time $T_{\text{cr}} \sim (1-3) \cdot 10^8$ yr corresponds to a value $D \sim 10^{28}$–10^{29} cm^2/s. Analysis of data on the chemical composition of the cosmic rays on the basis of a diffusion model leads to coefficients D of specifically this magnitude, thereby justifying the estimate used for T_{cr}. As we have already mentioned, this is an entire field—here one takes account of the energy dependence of the diffusion (and of the chemical composition), radioactive secondary nuclei (primarily, ^{10}Be nuclei), and much else. Another aspect of the problem is to go beyond the diffusion approximation and to construct diffusion equations from more-general kinetic equations describing the motion of charged particles (in particular, cosmic rays) in electromagnetic fields—more specifically, in the galactic magnetic field, with allowance for the regular and random components of the field. Again, we are talking about an entire field of research (see, for example, Chapter 8 in Ref. 5, Ref. 30, and the bibliography there). Bordering this field of research is yet another broad field of research: analyzing the mechanisms and processes for the acceleration of charged particles.

The acceleration of charged particles in space, as in nearly all known cases, is of an electromagnetic nature.[9] In other words, the acceleration is caused by electric fields, but the role played by the magnetic field is usually also just as important, although the energy of the charged particle is not altered by the magnetic field itself. Depending on the particular situation and conditions, one makes a distinction among betatron acceleration (which is caused by the induced electric field which arises as a result of a time variation of a magnetic field), acceleration in electrical double layers, acceleration upon the reconnection of magnetic field lines, the acquisition of energy in the interaction of particles with plasma waves (with a plasma turbulence), and, finally, the regular and statistical acceleration by moving magnetic inhomogeneities, in particular, the fronts of shock waves. We refer the reader to the reviews (see Chapter 9 in Ref. 5; see also Refs. 6, 32, and 33) and will content ourselves with simply a few comments here.

Work carried out by Fermi (1949, 1954; Ref. 34) has proved to be particularly important for analyzing the problem of the acceleration of cosmic rays. Attention was originally focused on statistical acceleration (second-order acceleration). Specifically, studies were made of collisions of a charged particle with magnetic inhomogeneities in random motion ("clouds"). The average statistical acceleration thus resulted, in particular, from the circumstances that the probability for "head-on" collisions is higher than that for "overtaking" collisions. When an average is taken over all collisions with inhomogeneities which have an isotropic velocity distribution, the result is a change in the energy of the particles[4,5,32,34]:

$$\frac{\mathrm{d}E}{\mathrm{d}t}=\alpha E, \quad \alpha=\xi\,\frac{u^2v}{c^2l}\,, \qquad (15)$$

where u is the average velocity of the clouds, v is the velocity of the accelerated particle, l is the mean free path between collisions, and ξ is a numerical factor which depends on the magnetic field configuration, etc. (the value $\xi=4$ is given in Chapter 9 in Ref. 5). The power-law spectrum observed for cosmic rays can be explained under the assumption that the particles are accelerated for a time T which is independent of the energy. If losses are ignored, we would then find from the equation $\mathrm{d}N/\mathrm{d}t=-\alpha N-(N/T)$ a spectrum $N(E) = KE^{-\gamma}$ with $\gamma=1+(1/\alpha T)$. Since γ is independent of the nuclear species, we must take the acceleration time T to be the time over which the cosmic rays escape from the system. Taking $\gamma\sim 3$ and $T=T_{\rm cr}\sim 10^8$ yr, we find $\alpha\sim 1/T_{\rm cr}\sim 3\cdot 10^{-16}$ s^{-1}. However, we have $\alpha\sim 4u^2/cl$ [see (15)], and the velocity of the magnetic-field inhomogeneities (clouds) in the local galaxy is $u\sim 10^6$ cm/s, so we would need $l\sim 4u^2/c\alpha\sim 3\cdot 10^{17}$ cm. For large inhomogeneities in the local galaxy, a more likely figure is $l\sim$ 3–10 pc$\sim$(1–3)$\cdot 10^{19}$ cm. Approximately the same value follows if we adopt a diffusion coefficient $D\sim cl/3\sim 10^{29}$ cm^2/s. The main point is that at small values of α the time $T_{\rm cr}$ is not long enough for any substantial acceleration of a particle. On the basis of considerations of this sort, interstellar acceleration was at one time regarded as clearly ineffective.[4] The situation is actually quite a bit more complicated, since there is an entire spectrum of inhomogeneities, and in principle interstellar acceleration might play a substantial role. In order to evaluate this role we need to relate the acceleration of the particles to their diffusion which occurs among the same inhomogeneities and to make use of observational data concerning the dependence of the relative numbers of secondary nuclei in the cosmic rays (Li, Be, B, etc.) on their energy. If interstellar acceleration is important, we would expect[35] an increase in the relative number of secondary nuclei with increasing energy. Observations reveal the opposite dependence. Furthermore, even when we allow for acceleration at shock fronts, which we will be discussing below, interstellar acceleration appears to be impossible at energies $E\gtrsim 10^{14}$ eV or even at $E\gtrsim 10^{12}$ eV (Ref. 36).

It is obvious from the essence of the matter and also formally, from Eq. (15), that the statistical mechanism (the Fermi mechanism) is particularly effective in regions which have inhomogeneities of small scale (of the order of l) which are moving rapidly (at high velocities u). Generally speaking, acceleration in the envelopes of supernovae corresponds to precisely such conditions. For these and other reasons, supernova envelopes have been and continue to be studied[4–6,17,29] as the most likely sources of galactic cosmic rays. We will come back to this question.

At this point we would like to turn to the most important achievement in research on the mechanism for the acceleration of cosmic rays over the past decade. We are talking about acceleration by shock waves which are propagating through a magnetotubulent plasma (see Ref. 37) and the reviews in Refs. 32 and 33). When particles are reflected from moving "walls" (regions with a strong magnetic field), the energy of a particle varies in accordance with the following law (we are ignoring terms of the order of u^2/c^2):

$$\frac{\mathrm{d}E}{\mathrm{d}t}=-2\,\frac{(\mathbf{u}\mathbf{v})\,v}{c^2l}\,E, \qquad (16)$$

where u is the velocity of the wall. In a single collision, the acceleration is proportional to u/c (an acceleration or, more precisely, energy change of first order), but when an average is taken over the angle between $\mathbf{u}$ and $\mathbf{v}$ there is no first-order acceleration in the isotropic case, and we are left with only the second-order acceleration, (15). If a particle is "trapped" between two walls which are closing on each other, there will, of course, be a first-order acceleration, but it will be limited to the time required for the walls to collide. Accordingly, first-order acceleration was previously regarded as being of only extremely limited importance in astrophysics. The situation changes if a shock wave (wall) is moving in a magnetoturbulent plasma. In this case, a first-order acceleration occurs at the wavefront.[10)] Such a particle then reaches the front again as a result of scattering by magnetic inhomogeneities ahead of or behind the shock front; the particle again acquires an increase in enegy; etc. As a results, accelerated particles with a power-law spectrum appear. Shock waves produced in supernova explosions and for other reasons are propagating in interstellar space. In principle, therefore, acceleration in interstellar space might thus turn out to be extremely effective. As we have already mentioned, however, this is not actually the case, aside from a certain "supplementary acceleration" of particles[38] which are accelerated primarily in compact sources.

We can and must use a halo galactic model for a brief discussion of one more very important question: the nature of the primary sources of cosmic rays in the local galaxy. Since with the pioneering study by Baade and Zwicky (1934; Ref. 39), supernova explosions have been regarded as sources of cosmic rays. During a supernova explosion, a kinetic energy $\sim 10^{49}$–10^{52} erg is released in the envelope, and such explosions occur every 10–30 yr in the local galaxy. The average rate of energy release for supernovae is thus $L_{\rm sn}\sim 10^{40}$ erg/s and probably $L_{\rm sn}\sim 10^{41}$–10^{42} erg/s. In order to maintain a quasisteady state with regard to cosmic rays in the local galaxy, we would need (Table III) the injection of cosmic rays at a rate (luminosity) $U_{\rm cr}\equiv L_{\rm cr}\sim(1\text{–}3)\cdot 10^{40}$ erg/s. From the energy standpoint, supernovae are thus capable of providing the required acceleration of cosmic rays. The hypothesis that supernovae play such a role received great support in 1951–1953, when data on radio emission made it clear that there were a large number of relativistic electrons in supernova envelopes. Finally, soon after the 1967 discovery of pulsars it was learned that some pulsars are in supernova envelopes. In particular, the pulsar PSR 0531 is undoubtedly a neutron star remaining from the supernova explosion in 1054 which led to the formaiton of the Crab Nebula. This pulsar is also responsible for the observed activity of the Crab Nebula.

There is accordingly no doubt that supernovae are intense sources of cosmic rays. Stars of various types also generate cosmic rays, but usually at an incomparably lower rate. For example, the average rate of cosmic-ray generation by the sun is $L_{\mathrm{cr},\odot} \sim 10^{25}$ erg/s. Consequently, even 10^{11} stars generating at such a rate would provide only $L_{\mathrm{cr}} \sim 10^{36}$ erg/s, or four or five orders of magnitude less than the value needed, $L_{\mathrm{cr}} \sim (1-3)\cdot 10^{40}$ erg/s. Certain stars (of type O, for example) are of course considerably more active than the sun, but there are not many of them. In general, although this point has not been proved rigorously, it seems extremely likely that neither nonexploding stars nor novae can compete with supernovae as the primary sources of cosmic rays.

The problem of the source Cygnus X-3 (Cyg X-3) is one of special importance. As we have already mentioned, this source generates cosmic rays at a rate[11)] $L_{\mathrm{cr}} \sim 10^{39}$–$10^{40}$ erg/s. Consequently, one or a few such sources would be capable of providing the genration rate required for the entire local galaxy. Since photons with an energy ranging up to at least 10^{16} eV are observed from Cyg X-3, it is clear that the protons which generate them (protons are the most likely) have an energy ranging up to 10^{17}–10^{18} eV. This circumstance is also extremely important, since the acceleration of particles with energies $E \gtrsim 10^{15}$ eV in the local galaxy, even in supernovae, has always been, and remains, a problem. We do not know, however, just how many sources of the Cyg X-3 type there are at a given time (possibly, there is only one) and just how long they emit. We need to stress that by itself the luminosity $L_{\mathrm{cr}} \sim 10^{40}$ erg/s, although huge, of course (the total luminosity of the sun is $L_{\odot} = 3.86\cdot 10^{33}$ erg/s), is completely comparable to the strength of supernovae. In fact, during the conversion of 10^{49}–10^{52} erg into kinetic energy in a supernova explosion, up to 10^{51} erg may be transferred to cosmic rays. If the acceleration process lasts even 3000 yr, we find a luminosity of specifically $L_{\mathrm{cr}} \sim 10^{40}$ erg/s. In the case of the Crab Nebula we know that the generation of cosmic rays has already lasted 1000 yr, is occurring today at a luminosity $L_{\mathrm{cr}} > 10^{38}$ erg/s (the strength of the electromagnetic radiation is $L \sim 10^{38}$ erg/s), and is related to the activity of the pulsar PSR 0531. The source Cyg X-3 is apparently a young pulsar[12)] in a binary system. It is quite possible that this is the product of some supernova explosion. The new information that the source Cyg X-3 provides in this regard is thus the indication that a pulsar may generate protons at a rate up to 10^{40} erg/s and with an energy $E \sim 10^{17}$–10^{18} eV. Earlier, it had appeared that a cosmic-ray generation rate of this magnitude was associated with an envelope or, in any case, not with the pulsar itself. Incidentally, opinions of this sort do not raise any objections even today, since sources of the Cyg X-3 type and, in general, binary sources with pulsars apparently form in only a small fraction of supernova explosions.

In one way or another, the research on supernovae, their evolution, and their emission is intimately related to cosmic-ray astrophysics and γ-ray astronomy. Much is still unclear here. For example, why does the luminosity of a source decay? One explanation is that there is a decrease in the rotation velocity of a pulsar remaining after the explosion. For the supernova SN1972E (in the galaxy NGC 5253), however, an exponential decay of the luminosity has been observed. Such a decay would be explained in a more natural way in terms of a radioactive decay of explosion products. These radioactive products should emit γ lines. For example, ^{56}Co nuclei convert through K capture into ^{56}Fe, in a process accompanied by the emission of a line with $E_\gamma = 0.847$ MeV. The detection of such lines on future satellites will cast much light on the situation. For example, an instrument has been designed which would be capable of detecting γ lines from supernovae which have flared up in other galaxies, out to a distance $R \sim 10$ Mpc.

It is thus clear that study of the explosions of nearby supernovae—in the local galaxy and in the Magellanic Clouds—is particularly important. The lack of preparedness for studies of this sort, which we have already mentioned and which was exposed by the case of supernova 1987A (which flared up on 23 February 1987), is especially unfortunate with regard to γ-astronomy and neutrino measurements. As one eminent physicist pointed out in a conversation with me, the observations of SN1987A were only a "general rehearsal" and will lead to improvements in the entire system for observations of flareups in the future. We do hope that this turns out to be the case, but, unfortunately, it is quite possible that no member of my generation will survive until "opening night." The probability for a flareup of yet another supernova in the local galaxy or in the Magellanic Clouds has of course not been reduced by the flareup of SN1987A, but this probability is no greater than one flareup in 10 yr or possibly 30 yr. It is thus even more important to attempt to learn even more about SN1987A in the Large Magellanic Cloud.[40] The star which exploded had a large mass, $M \sim 15\,M_{\odot}$; the mass of the envelope was of the same order of magnitude; the velocity of the envelope was also high, reaching $(2$–$4)\cdot 10^{9}$ cm/s (for the outer shells); and the kinetic energy of the envelope was $(1$–$3)\cdot 10^{51}$ erg. Cosmic rays in the envelope could be accelerated by three mechanisms: acceleration at the front of the outer shock wave, statistical acceleration by turbulent motions within the envelope, and acceleration by the pulsar (if one formed during the explosion, which is quite probable). In view of the rather large mass of the envelope and its high velocity, we would expect a high luminosity in cosmic rays (protons), reaching $L_{\mathrm{cr}} \sim 10^{42}$–$10^{43}$ erg/s. Many π^0 mesons and thus γ rays form not only at a rate of this magnitude but also at rates one or two orders of magnitude lower. The γ luminosity L_γ depends on L_{cr}, the cosmic-ray spectrum [we would naturally assume a power-law spectrum here, i.e, $N_{\mathrm{p}}(E) = KE^{-\gamma}$; it would have a maximum and would, crudely speaking, be cut off at some energy $E_{\min}$], and certain other factors.[22–41] Even at $L_{\mathrm{cr}} = 10^{40}$ erg/s and $\gamma = 2.1$–2.6, we would have $E_{\min} \sim 1$ GeV, and the flux of γ rays with $E_\gamma > 70$ MeV at the earth could be $F_\gamma(>E_\gamma = 70\ \mathrm{MeV}) \sim (3$–$6)\cdot 10^{-6}$ photon/(cm$^2\cdot$s). At the same luminosity L_{cr}, photons with $E_\gamma > 1000$ GeV, which could be detected on the basis of their Cherenkov radiation, should have a flux $F_\gamma(>E_\gamma = 1000\ \mathrm{GeV}) \sim 10^{-11}$–$10^{-10}$ photon/(cm$^2\cdot$s). Fluxes of this magnitude and even slightly lower could be detected by the installations presently in place in the southern hemisphere. With regard to γ rays with $E_\gamma > 70$ MeV, on the other hand, there might still be time to launch some instruments on balloons. The time for all such γ measurements is one or two years after the flareup. With regard to γ rays with $E_\gamma > 10^{15}$ eV, we note that even at $L_{\mathrm{cr}} \sim 10^{41}$ erg/s their flux at the earth from

SN1987A would be of the order of 10^{-14} photon/(cm^2·s) (if $\gamma = 2.1$) or 10^{-15} photon/(cm^2·s)($\gamma = 2.3$), but here we are ignoring absorption by the thermal background radiation. Absorption would reduce the flux by a factor of 10–30, and furthermore it would be difficult to expect a luminosity $L_{cr} \sim 10^{41}$ erg/s for a long time. Also small is the probability for detecting neutrinos with a high energy $E_\gamma \gtrsim 10^{14}$ eV generated by cosmic rays in the envelope of SN1987A. We refer the reader interested in the details to Ref. 41, but we might point out that the most realistic possibility appears to be the detection of γ rays with $E_\gamma > 1000$ GeV from SN1987A. We have not been discussing the detection of γ lines here. According to Ref. 40, for example, a year after the flareup we would expect from SN197A a flux $F_\gamma(E_\gamma = 0.847$ MeV$) \gtrsim 3 \cdot 10^{-3}$ photon/(cm^2·s) from the decay of ^{56}Co. We hope that corresponding measurements can be carried out.

In the future, there should undoubtedly be a working system (see, in particular, Ref. 22) which will allow the next flareup to be studied promptly in all ranges of electromagnetic waves and also by neutrino telescopes (we need to consider both the low-energy region $E_\nu \sim 1$–10 MeV and the neutrinos with $E_\nu \gtrsim 10^{12}$ eV) and gravitational antennas.

5. SOME PROSPECTS FOR FUTURE RESEARCH

Research on cosmic rays both by direct methods (with, say, balloons or satellites) and by indirect methods (e.g., on the basis of radio-astronomy data) is developing quite slowly in comparison with the rate in many other fields in physics. For one reason or another, we have gone long years without finding answers to many questions—as is clear from the historical introduction at the beginning of this report and from the comments which have followed. For example, the question of evaluating the role played by metagalactic cosmic rays by a γ-astronomy method based on observations of the Magellanic Clouds and from measurements of the gradient of the γ luminosity in the local galaxy was raised in 1972 and 1975, respectively. Even the simpler method of measuring the gradient, however, has still not yielded completely definite results and will be debated at the present conference. Discussion cannot settle the matter here: New measurements are necessary, and they have not been carried out for several years now because of the lack of γ satellites. We will have to wait at least a few years more until the analysis of data from the planned launches of the Gamma and GRO observatories. Other projects (e.g., the planned DUMAND neutrino telescope) have been waiting for years and even decades.

Despite difficulties of this sort, research on cosmic rays is proceeding on a broad front. The present conference, with more than 800 reports, is better evidence of that than my words. The International Cosmic Ray Conferences (ICRCs) are held every other year and last two weeks. The original reports, which fill several volumes, are printed beforehand (by the beginning of the conference), while the invited and rapporteur reports are published somewhat later. All these proceedings of the ICRCs constitute the voluminous annals of research on cosmic rays, [6] as the participants of ICRC-20 are of course well aware. I have mentioned this point as an example for others. I do not know of more-productive or more-effective conferences, although I am familiar with several fields of physics and astrophysics.

What have been the most important achievements in the field of cosmic-ray astrophysics over the past ten years? I chose this particular time interval because a report similar to the present one was made to the 15th conference in 1977 (ICRC-15, Plovdiv, Bulgaria[18]). Which results rank as important and which as less important is of course usually a debatable and subjective matter. I understand this, and I do not claim to have any special wisdom here. Furthermore, over the past decade I have spent less time on cosmic rays than before. With that said, here is how these achievements look to me.

1. A more detailed study of the elemental and isotopic composition of the primary cosmic rays.

2. The observation of, and the beginning of research on, antiprotons.

3. The γ-astronomy observations on COS-B (1975–1982), which are only now being analyzed in detail. Here we have in mind research on both discrete sources and the galactic background.

4. The observation of photons with $E_\gamma > 10^{14}$ eV and up to $E_\gamma \sim 10^{16}$ eV from Cyg X-3 and possibly certain other sources. The debate continues in this arena, but then we could say the same thing about nearly every question.

5. Theoretical analysis of the acceleration of particles at the fronts of shock waves.

This list could undoubtedly be continued, but then it might become an enumeration of the very many studies which are being carried out.

What awaits us in the future? I am thinking not of the really long-range outlook (since, incidentally, I am rather lukewarm to futurology) but of plans up to the beginning of the next century (formally, up to 1 January 2001) or until the centennial of the discovery of cosmic rays (7 August 2012). Such an extrapolation does not seem particularly daring or purely speculative. After all, we are familiar with the history of research on cosmic rays for 75 years. We are also aware of plans for constructing several large installations, whose construction and use will fill many years. It is difficult not to believe that some surprises await us, possibly even some substantial discoveries. As an example of surprises of this sort we might cite the 1983 observation of some extensive air showers which are believed to have been generated by γ rays with energies up to 10^{16} eV emitted from the source Cyg X-3.

Here is a list of some directions and problems which are fairly clear and definite.

1. Further research is needed on the elemental and isotopic composition of the cosmic rays near the earth. Much work has always been carried out in this direction and is still being carried out. This work is covered fairly comprehensively at the ICRCs, particularly the present one. Since I myself am a bit distant from this field, I will simply mention the particular urgency of research on radioactive secondary nuclei (^{10}Be, ^{14}C, ^{26}Al, etc.) and on the energy spectra of various secondary nuclei. The Advanced Composition Explorer (ACE) and Astromag projects and probably some others promise substantial progress in this field.[12,42]

2. Research on the electron and positron components remains quite urgent, despite the progress which has been made.

3. The antiproton question is not clear. Measurements

of the spectrum of antiprotons need to be repeated. If there are indeed many antiprotons at low energies, $E_k \sim 0.1$ GeV (i.e., if the number of such antiprotons is significantly higher than the number of secondary antiprotons at $x = 5$ g/cm^2), the problem of the production of antiprotons remains unresolved (see Ref. 43 regarding the status of the question as of 1985; to the best of my knowledge, no substantial new results have been reported since then).

4. The entire region of ultrahigh energies, $E > 10^{17}$ eV and especially $E \gtrsim 10^{19}$ eV, has remained a special case for a long time now: Here the spectrum is not known (in particular, whether the spectrum is cut off at $E \gtrsim 3 \cdot 10^{19}$ eV is not clear), and the chemical composition and the anisotropy are not clear. Another question which remins essentially open is the origin of such particles, although at $E \gtrsim 10^{19}$ eV the metagalactic version is the most plausible one (see Chapter 5 in Ref. 5 and also Refs. 6, 13, and 14 for more details). Huge installations, covering areas ranging up to 10^3 km^2, should be constructed for studying cosmic rays with energies up to at least 10^{20} eV (Ref. 44).

5. We have already said quite a bit about the importance of γ ray astronomy to cosmic-ray astrophysics. In addition to the launching of the Gamma and GRO observatories, we also need some new observatories in roughly the same range, 30 MeV $< E_\gamma <$ 5–30 GeV, and we need to construct an apparatus for the range 5 GeV $< E_\gamma <$ 100–400 GeV (Ref. 45). Only then will the existing gap in the spectrum be filled between the measurements on satellites (COS-B, Gamma-1, and GRO) and the ground-based measurements which make use of Cherenkov radiation ($E_\gamma > 10^{11}$–10^{12} eV). Furthermore, the ground-based measurements (which make use of emission from the atmosphere) can detect only discrete sources. The program of measurements for the Gamma and GRO observatories is known. In large measure, and quite naturally, the measurements will be a matter of repeating, refining, and expanding the studies begun on the satellites SAS-II and COS-B. Here I would like to stress the need for also carrying out measurements at high galactic latitudes, in order to detect a γ halo of the local galaxy, which would result primarily from the scattering of relativistic electrons (the inverse Compton effect) by thermal photons in the halo (see Chapter 6 in Ref. 5; see also Ref. 46). There is an obvious need for studies of various discrete γ sources (molecular clouds, pulsars, etc.), a determination of their spectra, and a determination of their intensity variations. The same comments can be made regarding measurements in the region $E_\gamma \gtrsim 10^{11}$–10^{12} eV (Cherenkov emission in the atmosphere) and in the region $E_\gamma \gtrsim 10^{14}$ eV (extensive showers).[13)] The source Cyg X-3, as well as other sources, warrants observations in all electromagnetic ranges as well as underground observations, which would serve to detect any sort of nonphoton radiation (its existence seems extremely dubious, but we cannot set out with a closed mind; we also need to search for what seems unlikely).

6. When we take indirect effects into account, we can say that nearly all directions in astrophysics are interrelated. There seems no point in presenting a detailed list here. Since they are relatively close to cosmic-ray astrophysics (or even make up part of it), we will cite only research on solar cosmic rays, a modulation of cosmic rays in the solar system, radio-astronomy studies of galactic halos (especially at wavelengths $\lambda \gtrsim 1$ m) and supernova envelopes, and some joint x-ray and radio observations of galaxies (measuring magnetic fields through a comparison of the inverse-Compton x radiation and synchrotron radio emission)

7. The most important new direction of research on cosmic rays far from the earth is the detection of neutrinos with very high energies, $E_\nu \gtrsim 10^{12}$ eV, generated by cosmic rays. Unfortunately, while a corresponding project, DUMAND, has been under discussion since 1975, it is apparently still quite far from realization. The same is true of some other well-known projects, with the possible exception of the installation at Lake Baĭkal. The situation as it stood in 1984 is reviewed in Chapter 7 of my monograph[5]; several results have also been reported at all the recent ICRCs,[6] and the present conference is no exception. Since I myself coauthored only one study in this field,[47] and since neutrino astrophysics as a whole is not my bailiwick, I cannot claim any particular objectivity. The situation is that research on high-energy neutrinos is to me an exceptionally interesting and important branch of astrophysics. The circumstance that for all these years it has not been possible to obtain the rather modest facilities required for implementing the DUMAND project or similar projects seems to be simply a matter of blindness on the part of scientific organizers. However, it is difficult not to believe that even before the anniversaries that we mentioned above the field of high-energy neutrino astronomy will begin to live not exclusively on paper, or, more precisely, it will enter the observation phase.

8. Cosmic-ray astrophysics, like all astrophysics, would be unthinkable without a theoretical side. Fermi taught us a good lesson here some time ago.[34] Much has been done in the theoretical realm, particularly over the past decade. We are thinking of the analysis of the propagation and acceleration of relativistic particles in a turbulent magnetized plasma and much else. The holdup usually results from gaps and uncertainties in the observational data. In general, it is sufficient to say that cosmic-ray astrophysics has a reliable theoretical side, and in general it is not the theory which is holding up progress.

What we have had to say in this section of the report is of course not a program of work or even a plan for such a program. We have simply listed some well-known problems. Our purpose has been to stress that cosmic-ray astrophysics and the related directions of research today constitute a well-branched and developed field of research. At the same time, it is perfectly clear that there is much else which must and can be done. Moving forward will require a major effort, however, and in this regard it will be important to have the understanding and assistance of the community of physicists and astronomers, the organizers of space research, and indeed of everyone on whom the development of science depends. One would hope that this conference and, in particular, my introductory report, will promote such an understanding.

I would like to take this opportunity to thank V. S. Berezinskiĭ, V. A. Dogel', and V. S. Ptuskin for comments and advice.

SUPPLEMENT

The purpose in publishing this report is to acquaint a fairly wide audience of physicists and representatives of related specialties with the development of cosmic-ray astrophysics and its present state. This field of physics and astronomy has grown so much, and on the whole is progressing so rapidly, that (as in several other cases) the nonspecialist is finding it progressively more difficult to stay informed and to see the forest despite the trees. At the same time, many are striving (quite reasonably, it seems to me) to follow the remarkable successes of astronomy, including cosmic-ray astrophysics and γ astronomy.

In this report I have tried to demonstrate, without going into details, just how much has already been done, how wide the spectrum of problems presently being discussed is, and what the outlook and problems for future research are. There is so much material, however, that the picture drawn here is slightly deficient, despite my wishes. It thus seems appropriate to use this supplement (first) at least to list the sections into which the program of the conference has been divided. This division was naturally reflected in those six volumes of the proceedings which were passed out to the participants of the conference just before it began. We will then make a few comments about the questions which are being discussed.

1. 20th International Cosmic Ray Conference (20th ICRC).

The total material was divided into three parts (this is true of both the published conference proceedings and the conference program).

Origin of cosmic rays; galactic phenomena (code OG, Vols. 1 and 2)

1. γ bursts
2. γ rays from point sources; diffuse radiation with an energy $E_\gamma \leqslant 3\cdot 10^{11}$ eV
3. γ radiation with an energy $E_\gamma > 3\cdot 10^{11}$ eV
4. nuclei in the cosmic rays with energies $E \leqslant 10^{12}$ eV/nucleon (composition, spectra, anisotropy)
5. nuclei in the cosmic rays with energies $E > 10^{12}$ eV/nucleon (composition, spectra, anisotropy)
6. electrons, positrons, antiprotons
7. propagation in interstellar space; nuclear interactions
8. acceleration and sources of cosmic rays
9. methods and apparatus
10. various

Phenomena at the sun and in the heliosphere (SH; Vols. 3 and 4)

1. acceleration of particles at the sun
2. high-energy charged particles and neutral emission in solar flares
3. Propagation of solar cosmic rays in the corona and in interplanetary space
4. acceleration of particles and their propagation in the heliosphere
5. composition (elemental and isotopic compositions; ionization) of particles of solar and heliospheric origin
6. long-term modulation of the galactic cosmic rays; the anomalous component
7. transition and atmospheric effects for primary and secondary cosmic rays
8. geomagnetic and atmospheric effects for primary and secondary cosmic rays
9. cosmogenic nuclides
10. solar neutrinos
11. methods and apparatus
12. various

High-energy proceses (HE; Vols. 5 and 6)

1. high-energy interactions
2. hadronic and electromagnetic cascades
3. extensive air showers
4. muons
5. neutrinos
6. new particles and processes
7. methods and apparatus
8. various

Each volume runs from 420 to 530 pages (there are a total of 2890 pages). A total of 852 reports are published in these volumes (only in abstract form, in some cases). Many new results were reported at the conference itself. On the other hand, the published reports whose authors did not attend were usually not discussed. The last three days of the conference (which took a total of 12 working days, some not filled) were devoted to rapporteur reports (of which there were 19). There were also some invited reports:

V. L. Ginzburg, (the report printed above);

M. M. Shapiro, "75 years of research on cosmic rays";

D. N. Schramm, "Nucleosynthesis in stars";

C. De Jager, "High-energy processes in solar flares";

Ya. B. Zel'dovich, "The universe: yesterday and today";

L. B. Okun', "Fundamental interactions: from pions to vions";

E. C. Stone, "Interplanetary research away from the ecliptic plane";

P. Povinec, "Research on cosmic rays through the use of 'cosmogenic' radioactive nuclei";

H. R. Rubinstein, "The present status of quantum chromodynamics in research on cosmic rays";

G. Volk, "Acceleration of particles in astrophysical shock waves."

We might add to this list the reports by J. A. Simpson, "Acceleration of cosmic rays in the outer heliosphere," and R. Z. Sagdeev, "Processes near Halley's Comet as a model for Fermi acceleration by galactic shock waves," although these reports were designated "highlight" reports. Furthermore, there were sessions devoted to collisions of relativistic ions, ultrahigh-energy γ astronomy, and neutrinos from supernova SN1987A. Finally, various workshops were held.

The invited and rapporteur reports and also certain others will be published in the future, making up three more volumes.

All this information is being presented here both to inform the reader and to illustrate the scale and scope of the range of problems discussed and of the entire field to which the conference was devoted. These conferences are held approximately every other year (the next, ICRC-21, is scheduled for January 1990 in Adelaide).

There is a point which needs to be stressed here: Cosmic-ray astrophysics (or, more precisely, that part of it to which my report was devoted) corresponds to only about a third of the entire set of problems which have been discussed at this and other conferences in the ICRC series. All three sections (OG, SH, and HE) which we discussed above are of course interrelated in one way or another. The nature of these relationships differs from case to case and is not always immediately obvious. For example, it has been asked on more than one occasion just why a conference on cosmic rays pays so much attention to the sun and the heliosphere. It might appear that these topics would be more pertinent at special conferences on solar physics and space research. Here is the answer: Solar cosmic rays, like other "products" of solar activity and processes at the sun and in the heliosphere, are undoubtedly characterized by a substantially lower release of energy and by substantially lower energies of the charged particles and photons which are emitted. On the other hand, the proximity of the sun and the heliosphere makes possible observations and measurements which are blessed with a wealth of detail which we can only dream about in the cases of the interstellar medium, stars, and supernova envelopes, not to mention quasars, galactic cores, and radio galaxies. Research on the sun and the heliosphere thus plays a role for the galactic and metagalactic astrophysics of cosmic rays, radio astronomy, and γ-ray astronomy which is similar to the role which laboratory research plays for the physics of plasmas in space or the role which laboratory spectroscopy plays for optical astronomy. As a more specific example we might cite the research on shock waves in the heliosphere (and even, say, near Halley's Comet), carried out to test a theory for the acceleration of particles in shock waves. When we instead consider the relationship between cosmic-ray astrophysics (OG) and high-energy physics as studied in cosmic rays (HE), we see that it is fairly obvious. For example, research on extensive air showers (EAS) serves on the one hand to reveal several interaction processes and their particular features at high energies. On the other hand, the same showers are used to analyze the composition, spectrum, and anisotropy of the primary cosmic rays with high and ultrahigh energies.

In brief, this multifaceted approach—the joint discussion (within certain limits) of all problems associated with cosmic rays—is fruitful and completely justified. That it is "impossible to comprehend the incomprehensibly vast," that something must be sacrificed, that choices have to be made—that is all another matter. It is thus not surprising that we see a gradual shift of accent from conference to conference. For example, even only ten years ago, at the 15th ICRC, that a special subsection was devoted to x-ray astronomy, but today there is no such subsection. Designs of various new instruments and installations have been discussed fairly extensively at the ICRC conferences. As these projects begin to see life, the results will of course also come under discussion.

On the whole, the ICRCs play a huge role in the development of the entire field. In this regard, the ICRCs can serve as a good example for other directions in physics and astronomy.

2. A few comments regarding the results of the conference with regard to cosmic-ray astrophysics.

At conferences which are held regularly and prepared beforehand, center stage is usully taken not by sensational events but by a comparison of new data and reports and discussions of details and designs for new apparatus. This is what happened at the present conference. The observations of SN1987A were of course not forgotten. The situtation with regard to the γ-astronomy observations of the envelope of this supernova is that they have not yet been carried out; the possibilities which are opening up were discussed briefly in the text of my report. With regard to the sensational observations of neutrinos from SN1987A, on the other hand, we note that this is a special topic, which we will not dwell on here, although it did receive much attention at the conference (it can be assumed that a corresponding review will be published in Usp. Fiz. Nauk).

Another of the most widely discussed questions was that of observations of γ rays with high ($E_\gamma > 3\cdot 10^{11}$ eV) and ultrahigh ($E_\gamma > 10^{14}$–10^{15} eV) energies. Binary sources are attracting particular attention: Cyg X-3, Her X-1, Vela X-1, the "black-hole candidate" Cyg X-1 and certain others. All this is a topic for a special review (a review being prepared by V. A. Dogel' and the present author is intended to serve this purpose, in part). Here we will limit ourselves to a few comments concerning Cyg X-3, i.e., the best-known source of this type. This source is clearly a time-varying source, so it becomes an extremely difficult matter to compare observations made at different times; or, more precisely, such comparisons tell us little. In the past two years, the level of γ emission from Cyg X-3 at $E_\gamma > 10^{14}$–10^{15} eV has apparently been extremely low. This circumstance has in fact generated some doubt that radiation of this sort has ever been seen from Cyg X-3. In the opinion of the rapporteur (R. J. Protheroe), however, a comparison of different measurements carried out at the same time over several years makes an emission from Cyg X-3 at ultrahigh energies look completely realistic (although, and we repeat, this emission does not occur *all* the time). There is no doubt that further observations are required, particularly at large installations. It would be particularly important to identify extensive air showers produced by specifically γ rays. Attempts are being made to do this, with the understanding that the extensive air showers genrated by γ rays should be relatively deficient in muons and should also differ from extensive air showers of nuclear origin in certain other characteristics. Unfortunately, these are directions in which we do not yet have reliable data. Consequently, if we approach the problem very rigorously, the existence of γ radiation at ultrahigh energies from Cyg X-3 and possibly from other sources has not yet been proved. It is obvious that no far-reaching assertions can be made without further observations. At the level of impressions and opinions, on the other hand, I share the opinion that a sporadic γ emission does occur from certain binary sources at ultrahigh energies ($E_\gamma > 10^{14}$–10^{15} eV).

The continuing discussion of the COS-B data makes it look extremely likely that there exists a gradient, possibly not large but significant, in the density of cosmic rays in the local galaxy. In any case, the assertions of a clear absence of a gradient and even of a metagalactic origin of the cosmic rays were not repeated at the conference. Only new observations can lead to a reliable measurement of the gradient and, more generally, of the distribution and spectrum of the cosmic rays (primarily protons) in the local galaxy.

New observations (E.A. Bogomolov *et al.*, report OG6.1-1) and calculations (W. Weber, report OG6.1-5) make the problem of antiprotons less acute—these new results proide evidence that the number of antiprotons at energies $E_{\bar{p}} > 1$ GeV is possibly not anomalously large (i.e., it may turn out to be consistent with that expected in the case in which cosmic rays traverse interstellar gas of thickness $x \approx 5$–7 g/cm^2). An anomalously high flux of antiprotons at energies $E_{\bar{p}} \sim 0.1$–0.3 GeV (we are talking about the kinetic energy, of course) was reported in only a single paper [A. Buffington *et al.*, Astrophys. J. **248**, 1179 (1981)], and this high flux cannot be accepted as an established fact until there is an independent test (to the best of our knowledge, measurements of this sort are presently being carried out in the USA).

The first results of an analysis of the data obtained from The Egg package which flew for 191 hr on the Space Shuttle (Spacelab 2) in 1985 were reported at the conference (see the text of my report and also reports Og4.1–5 and OG9.2–1). Characteristically, we have had to wait two years since the flight to obtain results—preliminary results—about the spectrum at energies ranging up to 10^3 GeV/nucleon, despite the use of the most sophisticated, state-of-the-art apparatus. It is thus clear just how complicated the corresponding observations are and just how laborious it is to analyze the results. In order to find the spectra of nuclei up to energies of the order of 10^4–10^5 GeV/nucleon, we will need even larger installations, weighing tens of metric tons. This is a matter for the future (such results could hardly be expected in less than ten years or so).

With regard to the elemental and isotopic composition of the cosmic rays at lower energies (at, say, $E \lesssim 10$ GeV/nucleon), and the spectrum of positrons, several results were reported and discussed at the conference. In my report, however, this important circle of questions was only touched on, and nothing dramatically new was reported at the conference. Accordingly, this is not the place to go into either problem of the composition and spectrum of the cosmic rays or several other problems which are reflected in the conference proceedings (the proceedings, incidentally, are quite accessible in our country, since the conference was held in the USSR, and all of its many particupants received a complete set of volumes).

I will thus conclude with the one comment that participation in the conference did not move me to alter anything substantial in the text of the report printed above. Within the limited scope intended for this report (and, or course, within the limits of my capabilities), it does reflect the present status of cosmic-ray astrophysics (in addition to questions concerning solar cosmic rays and processes in the heliosphere).[14]

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[1] Report prepared for the 20th International Cosmic Ray Conference (Moscow, 2–15 August 1987). There has been essentially no change in the text of the report for this paper. There is, however, a supplement at the end of the paper which gives an idea of the work of the conference.

[2] The "primary" cosmic rays are those which are outside the earth's atmosphere. We will be discussing only the primary cosmic rays below, not the products of their decay and breeding in the atmosphere. We will thus usually be omitting the adjective "primary."

[3] At the earth's surface one also observes a secondary neutron component of the cosmic rays. Its flux amounts to about 1% of the flux of the muon component. The neutron component is produced primarily by primary particles with energies considerably lower than the energy of the muons which reach the earth. Furthermore, the flux of the neutron component, in contrast with the muon flux, is essentially independent of the temperature distribution in the atmosphere. The net result is that study of the neutron component is convenient for detecting time variations of the intensity of the primary cosmic rays with an energy of several GeV. A continuous detection of the intensity of the neutron component of the cosmic rays is being carried out by a network of stations at many points around the world.

[4] The time T introduced here is defined by $T = x/c\rho$ and has a physical meaning only if a model is specified. For example, if the disintegration of nuclei occurs essentially exclusively in the gaseous disk (i.e., if the halo is inconsequential from this standpoint), the time T would be the time spent by the cosmic rays in the disk.

[5] One such method, which is still being used only rarely, but which is promising, is as follows: One can determine the spectrum of the electron component from the spectrum of the x-ray emission, which the electron component produces as a result of the so-called inverse Compton scattering by a known radiation field, say the 2.7 K background radiation. The quantity LK_e in (9) is then known, and by measuring the radio-emission intensity J_ν from the same region, one can find the field H in this region, again from Eq. (9).

[6] As often happens, positive and negative results do not lead to directly opposite conclusions here. For example, the presence of a clearly defined gradient in the cosmic-ray density in the local galaxy (with the density falling off with distance from the galactic center) would be clear evidence of a galactic model and would contradict metagalactic models. If, on the other hand the gradient is, say, totally imperceptible, then this result still does not contradict galactic models if it is assumed that such models are "closed" (we have in mind the presence of a strong reflection of the cosmic rays at the houndaries or, more precisely, the periphery of the halo). Consequently, the magnitude of the gradient undoubtedly must be known in order to refine a halo model.

[7] Such an extremely important parameter as the rate at which cosmic rays are generated in the galaxy, $U_{\rm cr} \equiv L_{\rm cr} \sim (1\text{–}3)\cdot 10^{40}$ erg/s, depends only weakly on the choice of model. The situation is that here we have

$$U_{\rm cr} \sim \frac{W_{\rm cr}}{T_{\rm cr}} \sim \frac{w_{\rm cr}V_{c\bar{\rho}}}{x} \sim \frac{cw_{\rm cr}M_{\rm g}}{x} \sim 5\cdot 10^{-3}M_{\rm g} \sim 5\cdot 10^{40}\ \text{erg/s},$$

where $x = c\bar{\rho}\,T_{\rm cr} \sim 5\ \text{g}\cdot\text{cm}^{-2}$ is the gas thickness traversed by the cosmic rays, $\bar{\rho}$ is the average gas density, and $M_{\rm g} = \bar{\rho}_{\rm t} \sim 10^{43}$ g is the total mass of gas in the local galaxy. (The values $M_{\rm H} \sim 2\cdot 10^{42}$ g and $M_{\rm H_2} \sim 10^{42}$ g figure in the literature for the masses of atomic and molecular hydrogen, respectively; when other elements, and especially, ionized hydrogen, which is predominant in the halo, are taken into acount, the accepted value $M_{\rm g} \sim 10^{43}$ g seems completely reasonable). The rate at which cosmic rays are generated is sometimes called the cosmic-ray "luminosity" (and thus the notation $L_{\rm cr} \equiv U_{\rm cr}$).

[8] On the other hand, Eq. (14) ignores the possibility of a motion of the medium (the interstellar gas). When such motions are taken into account, we need to add a term div(N_i**u**) to the left side of Eq. (14), where **u** is the velocity of the medium (we also need to add a term to reflect the change in the energy of the particles as they move in a nonuniform flow). There are various fluxes in the local galaxy, particularly of a convection nature. Furthermore, we do not rule out the existence of a "galactic wind": gas which is escaping from the galaxy, or, say, escaping in certain directions and entering in others (we would thus be talking about a large-scale convection or circulation).

[9] As an important exception we should mention the acceleration of particles in a shock wave which is propagating in the absence of a magnetic field along the direction of decreasing density of matter in the atmosphere of a star. Under these conditions, the velocity of the wave can become relativistic, so all the particles behind the wavefront will acquire a high energy.[31] At the microscopic level, of course, it is specifically the electric field which determines the momentum transfer in collisions of particles but there may be no macroscopic electromagnetic field.

[10] At the front of a shock wave, the velocity **u** of the gas through which the wave is propagating changes, and the gas at the front is compressed. Near the front (which is slightly diffuse, because of viscosity and other factors), the condition div**u** < 0 holds. This condition corresponds to acceleration (see, for example, Chapter 9 in Ref. 5 for more details).

[11] The strength of the source Cyg X-3 apparently varies greatly in time. This circumstance and several others are responsible for the doubts which prevail regarding the data on Cyg X-3 (see the Supplement).

[12] There are indications that this pulsar is radiating γ rays with $E > 10^{12}$ eV at a period of 12.6 ms.

[13] This task will require installations of large area ($S \sim 1$ km^2), equipped with a sufficient number of muon detectors (required to distinguish muon-poor showers generated by γ rays).

[14] The references at the end of this paper are not intended to constitute a complete bibliography (obviously), and furthermore they are given only as guideposts (in addition, the sources from which the author borrowed some of the figures are cited).

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