Physics of Our Days

*COSMIC RAYS ON EARTH AND IN THE UNIVERSE**

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Primary cosmic rays on earth, their chemical composition, and energy spectrum. Radioastronomy and cosmic rays. Nature of cosmic radio emission and cosmic rays in the universe. Origin of cosmic rays.

SOME 50 years ago it was established that a "radiation," called cosmic rays, reaches the earth from outer space. This radiation was found to be highly penetrating, and even thick layers of lead failed to stop it.

The discovery of cosmic radiation was the result of an investigation of the "dark" current in ionization chambers. The fact that current flows in ionization chambers in the absence of any artificial ionization sources (this precisely is the dark current), was observed at the very beginning of the century. Its appearance in ionization chambers located near the earth's surface could be ascribed to radioactive impurities in the objects surrounding the chamber. The cosmic (extraterrestrial) origin of some part of the dark current was therefore proved only after experiments had been made with balloons. The current produced in the ionization chamber by the radioactivity of the earth and various objects should decrease with increasing distance from the chamber to the earth's surface. It was found, however, that the ionization current decreased with rising altitude only up to a certain low level, beyond which it began to increase. Thus, in experiments carried out in 1914, the ionization was found to be much higher at an altitude of 9 km than at sea level. To be sure, various hypotheses ascribing a terrestrial origin to cosmic rays were advanced even after these experiments; their appearance was attributed, for example, to thunderstorms and to radioactivity of the upper layer of the atmosphere. All these hypotheses, however, have long been set aside.

Because of their high penetrating ability, cosmic rays were first regarded as a modification of gamma rays. It was ascertained later on that the primary cosmic rays contained charged particles. This could be observed by using the earth's magnetic field, in which moving charged particles are deflected. As a result, the flux of primary cosmic rays, i.e., the rays incident on the earth's atmosphere, depends on the geomagnetic latitude. The primary cosmic rays produce in the atmosphere secondary particles and only the latter are observed on earth. The observed dependence of the flux of these particles on the geomagnetic latitude enables us to conclude that charged particles are contained in the primary cosmic rays. A direct investigation of the primary rays was practically impossible for a long time, because of the difficulty in raising the apparatus to high altitudes. The lack of reliable data on primary cosmic rays made it impossible to explain their origin, and the origin of cosmic rays was a moot question for many years.

The situation did not change much even after it was ascertained that the primary cosmic rays consisted of protons and nuclei of many elements (the presence of nuclei was established in 1948). The point is that cosmic rays have an isotropic distribution, i.e., they arrive on earth uniformly from all directions. Their investigation therefore yields no direct information on the location of the cosmic-ray sources. To better understand the extent to which the isotropy of cosmic rays makes difficult a determination of the origin, let us imagine that the optical radiation from all the celestial bodies is first mixed, and then analyzed. In this case, instead of investigating the spectrum and the intensity of the optical radiation from individual stars and nebulae, it would be necessary to investigate the same radiation characteristics, but from all these objects taken together. It is quite obvious that under the condition nothing would remain of modern astrophysics. Yet the information concerning the cosmic rays pertains precisely to all the sources taken together. An attempt at an analysis of this information is similar to attempting a spectral analysis of the overall light from all the stars and nebulae.

But can any information on cosmic rays in different parts of the universe far away from the earth be obtained at all?

Even relatively recently this question would have been answered in the negative. But, as happened many times in the history of physics and astrophysics, the situation changed rapidly and radically as a result of discoveries made in an utterly different field. Here we have in mind radio astronomy, the vigorous development of which began in 1945. It was found (in 1950 — 53) that the main part of the radio emission from

*Articles devoted to the origin of cosmic rays and to radio astronomy have already been published in Uspekhi Fizicheskikh Nauk. In view of the great interest that is attached to this group of problems, the editor presents this article, written specially for the section on "Physics of Our Days."

space is generated by cosmic rays. By receiving the cosmic radio emission, we can establish certain properties of cosmic rays not only in our own galaxy, but far beyond its limits. The development of radio astronomy and the establishment of a connection between cosmic radio emission and cosmic rays has advanced the problem of the origin of cosmic rays and the manifestation of their properties in various regions of the universe to a prominent place in astrophysics. It became possible, as in the solution of other astrophysical problems, to make use of observational data, and to carry out the analysis by using an aggregate of data obtained by various means. Cosmic rays have proved to be interesting not only as an independent object of study, but, as has become clear in time, they play an important role from the point of view of the dynamics of the interstellar medium and the shells of supernovae, and are also one of the main factors in the determination of the evolution of galaxies.

Cosmic-ray physics almost always followed two clear-cut trends. The first was the use of cosmic rays for the study of elementary particles and their interactions at high energies. Essentially this involved merely the possibility, provided by nature itself, of observing high-energy particles. These possibilities were used with great success. It was in cosmic rays that the positrons, $\mu^{\pm}$, $\pi^{\pm}$, and K mesons, and also certain hyperons, were discovered. A study of these particles is of such great importance that for a long time, particularly from 1929 through 1955 or 1956, the investigation of elementary particles played the principal role in cosmic-ray physics. The situation changed radically with the development of powerful accelerators. At the energies afforded by accelerators (energy E up to 3×10^{10} ev) cosmic rays can in general hardly compete with accelerators as a tool for the investigation of elementary particles. The emphasis in the first trend of cosmic-ray physics has therefore shifted towards higher energies ($E > 3 \times 10^{10}$ ev). In this region, the measurements are carried out principally with the aid of photoemulsions and observations of extensive atmospheric showers. Inasmuch as the maximum energy registered in cosmic rays is approximately 10^{19} ev, it is quite obvious that the use of cosmic rays for purely physical researches will continue probably for a very long time.* Nonetheless, the relative "weight" of elementary-particle research has undoubtedly been greatly reduced, and recently a second trend has started to predominate in cosmic-ray physics, namely investigations of the geophysical and astrophysical aspects of cosmic rays. At the present time, the number of investigations in this direction amounts to more than half of all the researches devoted to cosmic rays. The study topics are:

1. Primary cosmic rays on earth (chemical composition, energy spectrum, lateral distribution).
2. Cosmic rays beyond the solar system (in the galaxy and metagalaxy).
3. Origin of cosmic rays.
4. Solar cosmic rays, their generation, motion towards the earth, and influence on the earth's ionosphere.
5. Effect of the interplanetary medium and of the interplanetary magnetic fields on cosmic rays (of both galactic and solar origin); high-latitude cut-off and different variations of cosmic rays, both on earth and beyond the solar system.
6. Radiation belts near the earth and other planets.

The launching of artificial satellites and space rockets, and also the general progress in geophysics and solar physics, on the one hand, and the rapid development of radio astronomy and astrophysics as a whole on the other, have given rise to many researches in all the aforementioned topics. All these researches are furthermore related not only with each other, but also with other scientific endeavors (solar physics, the physics of the interstellar and interplanetary medium, theory of particle acceleration, radio astronomy, etc.). It would be quite difficult and hardly advisable to attempt to discuss a large number of problems in a single article. We shall therefore touch upon only three problems: the properties of primary cosmic radiation on earth, data on cosmic rays in the universe (beyond the limits of the solar system), and the origin of cosmic rays.

1. PRIMARY COSMIC RAYS ON EARTH

The mass of a column of the earth's atmosphere 1 cm^2 in area is approximately 1 kg. Such an air filter, from the point of view of passage of various types of radiation, is equivalent to a layer of water about 10 meters thick. The mean free path of the particles contained in primary cosmic rays is less than one meter of water (less than 100 g/cm^2). This means that the atmosphere acts as a thick filter of primary cosmic rays and these rays practically do not reach the earth's surface. The situation does not change appreciably even on high mountains, where the primary particles amount to only a small fraction of the total flux of cosmic rays. A study of primary cosmic rays, the only rays in which we are interested, is possible only with the aid of pilot balloons, high-altitude airplanes, rockets, and artificial satellites. Until recently the princi-

*As indicated, the energy attainable with accelerators is at present 3×10^{10} ev, i.e., almost nine orders of magnitude below the maximum particle energy observed in cosmic rays. We can hardly expect to see in the near future development of accelerators producing particles of energy higher than 3×10^{11} ev. We recall, however, that the use of the so-called "opposing beam" method, while fraught with great difficulties, permits in fact investigation of collisions between particles with energy $E' = 2(E/Mc^2)^2 \times Mc^2$, where E is the particle energy in each beam, consisting of particles with rest mass M. However, even for electrons with $E = 5 \times 10^9$ ev, the energy is $E' = 10^{14}$ ev, and for protons we have $E' \simeq 2 \times 10^{12}$ ev at $E = 3 \times 10^{10}$ ev.

pal role was played by pilot balloons, but more research with the aid of satellites is expected.

To determine the chemical composition of the primary rays, the most widely used is the photoemulsion method, although Cerenkov counters are also used. It is important to emphasize that cosmic rays contain "bare" nuclei having no orbital electrons. In this case the ionizing ability and the intensity of the Cerenkov radiation, other conditions being equal, are proportional to Z^2, where Z is the atomic number of the element. Consequently nuclei with different Z produce different tracks in emulsion (Fig. 1). In a Cerenkov counter (Fig. 2), *the nuclei are differentiated by the intensity* of the Cerenkov-radiation flashes.

The energy spectrum of cosmic radiation (the dependence of the number of particles on their energy) is determined from the latitude dependence of the

FIG. 1. Emulsion tracks of relativistic nuclei with different Z. It is seen that the thickness of the track increases with increasing Z.

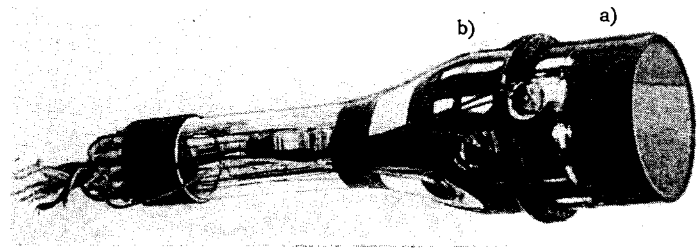


FIG. 2. Cerenkov counter a – Plexiglas detector, b – photomultiplier. The fast charged particles penetrating into the counter emits light (the Cerenkov effect) which is registered by the photomultiplier.

cosmic-ray flux. This method is limited to an energy range up to approximately 15 Bev for protons and up to 7.5 Bev/nucleon for nuclei.* At higher energies, the energy spectrum is determined, for example, from the number of particles having some specified energy, registered in the emulsion. This method yields certain data up to energies on the order of $10^{12} - 10^{13}$ ev. At still higher energies, the cosmic rays are investigated almost exclusively in connection with extensive air showers, which will be discussed later.

An investigation of the primary cosmic rays consists of determining their composition (i.e., the number of particles with different charges and masses), the energy spectrum of the particles of each kind, and their lateral distribution. All these problems have been far from exhaustively studied. But researches are being carried out by many groups in many countries, and there is no doubt that progress in this field will be rapid. We give below the principal results about which there is no special doubt.

a) Chemical Composition

Unfortunately, the determination of the charge of a given nucleus, say in emulsion, is subject to an appreciable error. In addition, even when the measurements

*Let us explain briefly why the energies of the protons and nuclei differ so much. The frequency of rotation of a particle with charge eZ, total energy E, and mass M in a magnetic field of intensity H is $\omega_H^* = (eZH/Mc)(Mc^2/E)$. The radius of curvature of the trajectory of this particle, if its velocity v is perpendicular to the field **H**, is equal to $r = v/\omega_H^*$; for relativistic particles we have $v/c \simeq 1$ (i.e., $E/Mc^2 = (1 - v^2/c^2)^{-1/2} \gg 1$), and $r = E/eZH$. In the latter case, if we measure r in centimeters, E in ev, and H in oersteds, we have

$$r = \frac{E}{300ZH} = \frac{A\varepsilon}{300ZH}, \qquad (1)$$

where $E = A\varepsilon$, A is the atomic weight, and ε is the total energy per nucleon.

Whether a particle can reach the earth depends obviously on the radius of curvature of its trajectory in the earth's magnetic field. For protons $A/Z = 1$, but for nuclei $A/Z \simeq 2$. Therefore the earth's magnetic field, while preventing protons with $E < 15$ Bev from reaching the equator (in a vertical direction), does not keep cosmic rays with energy $\varepsilon > 7.5$ Bev/nucleon from reaching the earth's equator.

are made in pilot balloons, a layer of air several grams per square centimeter thick still remains above the apparatus. Only in one case known to us did this layer amount to 2.7 g/cm^2 (altitude somewhat higher than 40 km). Usually, measurements are carried out at lower altitudes (layer thickness 7 — 15 g/cm^2). Investigations of nuclei with the aid of satellites have only begun. The presence of a layer of air above the apparatus causes part of the nuclei observed in emulsion (or by other methods) to be secondary, since they were formed in the air. Finally, to obtain sufficiently accurate values it is necessary to investigate tracks of many nuclei under identical conditions. This is particularly difficult in the case of rarely encountered elements. From all the foregoing it is easily seen that the information available on the chemical composition of primary cosmic rays is far from complete. In particular, to increase the statistical accuracy, data are usually given not for individual nuclei, but for entire groups. Thus, the nuclei of lithium, beryllium, and boron (Z = 3 — 5) form the group of light (L) nuclei. Carbon, oxygen, nitrogen, and fluorine (Z = 6 — 9) are combined into the medium-nuclei group (M). Nuclei with atomic number $Z \geq 10$ make up the heavy group (H); sometimes a group of very heavy (VH) nuclei with $Z \geq 20$ is also introduced. Protons (p) and H_2^4 nuclei, i.e., α particles (α), are considered apart from other nuclei.

The existing methods, disregarding the small number of slowest particles, cannot be used to determine the atomic weight of the nucleus. In other words, all isotopes of a given element are lumped together. Therefore, strictly speaking, the p group combines the protons, deuterons, and tritium nuclei, while the α group also includes the He_2^3 nuclei. For each of these groups we define the flux F, i.e., the number of particles incident on a unit area per unit time in a unit solid angle. (F is expressed below in particles/m^2-sr-sec; we note that it is more correct to call F the intensity or the flux in a given direction, but the term flux is more widely used.) The total flux F is obtained by integration over the angles; for isotropic radiation, integration over a hemisphere yields $F_n = \int F \cos\theta \, d\Omega = \pi F$). The fluxes of the foregoing particle groups are listed in Table I. The average atomic weight $\bar{A}$ for each group (third column of the table) is determined from the same experimental data that are used to determine the fluxes. We note that the values of F pertain in all cases to particles with total energy greater than 2.5 Bev/nucleon.

The sixth column of Table I lists the ratio of the flux of nuclei of a given group to the flux of the H-group nuclei; this ratio is at the same time equal to the ratio of the concentrations of the nuclei of the corresponding groups, N/N_H. It is taken into account here that for isotropic particle distribution we have $N = 4\pi F/c$, where v is the particle velocity. For the relativistic particles under consideration, we can write with sufficient accuracy $v = c = 3 \times 10^{10}$ cm/sec. The last two columns of the table give the ratios N/N_H obtained from various data, characterizing the average abundance of the elements in the universe—on the sun, on stars, and in the interstellar medium. As is clear from Table I, the chemical composition of cosmic rays has two striking singularities.

First, although the abundance of the light elements —lithium, beryllium, and boron is very low in nature, for these elements rapidly "burn up" in the stars, the elements of the L group are almost as plentiful in cosmic rays as the heavy elements (H group), i.e., approximately 100,000 times more abundant than in nature on the average.

Second, cosmic rays are much richer in heavy and very heavy elements than celestial bodies. In fact, in cosmic rays there are approximately 550 protons and α particles for each nucleus of group H, and approximately 2,000 protons and α particles for each nucleus of group VH (we shall see that in practice this group is made up of iron and chromium). At the same time, according to various data, there are 3600 — 8,000 protons and α particles in the universe for each nucleus of group H, and 60,000 — 160,000 for each VH nucleus. This means, even if the lower values 3600 and 60,000 are used, that cosmic rays are seven times richer in heavy elements and 30 times richer in very heavy elements than the sun, the stars, and the interstellar gas.

It is natural to interpret the presence in cosmic rays of lithium, beryllium, and boron in the following fashion. As the cosmic rays move in the interstellar medium, the nuclei of groups M and H are broken up

Table I. Chemical composition of cosmic rays
(The chemical composition of the interstellar gas is determined in general from the figures listed in the two last columns).

Group of nuclei	Z	$\bar{A}$	Number of particles / m^2-sr-sec	Number of nucleons in cosmic-rays flux (i.e., value of $\bar{A}F$)	$\frac{F}{F_H} = \frac{N}{N_H}$	In the universe (on the average)	
						N/N_H	N/N_H
p	1	1	1300	1300	520	3360	6830
α	2	4	88	352	35	258	1040
L	3—5	10	1.9	19	0.76	10^{-5}	10^{-5}
M	6—9	14	5.6	78	2.24	2.64	10.1
H	⩾10	31	2.5	78	1	1	1
VH	⩾20	51	0.7	35	0.28	0.06	0.05

by nuclear collisions with the nuclei of the atoms of the interstellar medium, i.e., essentially protons and helium nuclei. Among the products of such disintegrations are the group-L nuclei, which are thus secondary—the very low abundance of these nuclei in nature leads us to believe that they are also absent from the sources of cosmic rays. Taking into account the relatively large number of L nuclei in cosmic rays on earth, and assuming all these nuclei to be secondary, we can conclude that cosmic rays arrive from a great distance; on the average they should pass through a layer of matter $5 - 10$ g/cm^2 thick. The average concentration of gas in our galaxy is approximately 0.01 particle/cm^3, corresponding to a density 2×10^{-26} g/cm^3. It follows therefore that the cosmic rays travel on the average some 3×10^{26} cm before they reach the earth; moving almost with the velocity of light, $c = 3 \times 10^{10}$ cm/sec, the particles cover this path in about 10^{16} sec $\simeq 3 \times 10^8$ years.

The radius of our galaxy is approximately $R = 3 - 5 \times 10^{22}$ cm $\simeq 30 - 50$ thousand light years. Since the path covered by the cosmic rays (3×10^{26} cm) is much greater than the radius of the galaxy, the thought arises that the cosmic rays come from regions far beyond the galaxy. Such a conclusion, however, would be premature, to say the least. The point is that magnetic fields of intensity $H \sim 10^{-6} - 10^{-5}$ oe exist in the interstellar space. The radius of curvature of the trajectory of a proton with an energy typical of cosmic rays, say $E = 10^{10}$ ev = 10 Bev, is $r = E/300H \simeq 3 \times 10^{13}$ cm even in a field of 10^{-6} oe, i.e., it is negligibly small compared with galactic dimensions. When the radius is sufficiently small, the character of the motion of the cosmic rays in the galaxy is determined by the configuration of the interstellar magnetic field: a charged particle in a homogeneous magnetic field moves along a helical line, and its velocity along the field is equal to the component $v_{||}$ of the total velocity v along the field. We can therefore assume that on the average, over a sufficiently long time, the particle moves in the homogeneous field linearly with a velocity $v_{||}$. If the force lines of the field are bent and form a tangled "ball," the particle will move along a complicated trajectory; in first approximation this trajectory wraps itself around the force line. In "tangled" magnetic fields of complex configuration, the motion of a particle in any direction can be likened to the diffusion of molecules in a gas. The diffusing molecule describes a complicated trajectory, made up of linear segments equal to the mean free path, i.e., equal to the distances between the collisions of the given molecule with the atoms or molecules of the gas. The role of the mean free path in motion in a "tangled" magnetic field is played by the characteristic distance l, over which the direction of the force lines of the field changes appreciably (Fig. 3). Naturally, the analogy between diffusion in gas and motion in the magnetic field is limited, and becomes meaningful only if many conditions are satisfied. We can think that in galactic magnetic fields these conditions are satisfied with a certain degree of approximation.* Since the magnetic fields in the galaxy as a whole have in all probability a highly tangled character, the cosmic rays move along complicated paths, and most of them spend their entire "life" within the confines of the galaxy.

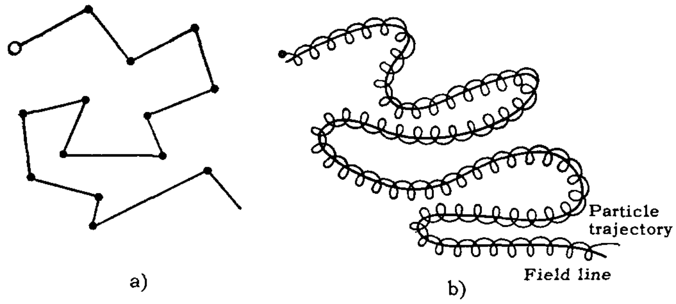


FIG. 3. a) Motion of a molecule in gas, b) motion of a particle in a magnetic field.

Returning to the problem of the chemical composition of the cosmic rays, we point out another important conclusion, which follows directly from the statement just made concerning the origin of the L nuclei. Inasmuch as these nuclei are disintegration products of heavier nuclei, it is clear that the cosmic-ray sources have even more heavy particles than there are on earth. A more detailed examination shows that in a layer of thickness $5 - 10$ g/cm^2, the very heavy nuclei, such as iron and chromium, could generate all the other particles present in the cosmic rays on earth. To be sure, the insufficient accuracy with which the chemical composition of the cosmic rays is known, and the lack of data on the products observed in nuclear collisions (for example, collisions between protons and iron nuclei) do not enable us to draw final conclusions. There is no doubt, however, that the heavy and very heavy particles (the latter being iron, chromium, etc.) are the ones essentially accelerated in the cosmic-ray sources. This means that the cosmic rays at the sources are even richer in VH nuclei than those on earth, at the expense of protons, α particles, and L nuclei, and probably also the M and H nuclei.

In addition to data on groups of nuclei, interesting information is available at present also concerning certain nuclei. Thus, there is more carbon than oxygen in cosmic rays, whereas in the universe, on the average, the situation is reversed. Although there is very little fluorine in nature, it has a noticeable abundance in cosmic rays. Finally, iron and chromium

*The success of the diffusion approximation is due to the fact that the trajectory of the particle is not at all firmly "stuck" to the force lines of the field. A slow transition takes place from one field line to others, first as a result of the so-called "drift" in the inhomogeneous field, and second because the magnetic field changes all the time as a result of the galactic rotation and the motion of interstellar gas clouds. The cosmic rays in the galaxy are thus apparently effectively "mixed," i.e., their average motion is like that in the diffusion process.

are predominant among the VH nuclei. An exact determination of the chemical composition of primary cosmic rays on earth is one of the most urgent problems in cosmic-ray physics. A major role will undoubtedly be played here by satellites.

In speaking of the chemical composition of cosmic rays, we had in mind, essentially, only the main part of the cosmic rays, with energy less than $10^{12}-10^{13}$ ev. There are practically no data at all on the chemical composition of the particles with higher energies.

It is also very important to know the number of electrons and positrons contained in the primary cosmic rays on earth. Unfortunately, one can merely indicate at present that, according to the rather old measurements on hand, the number of electrons and positrons is less than about 1% of all the cosmic rays. More exact information on electrons and positrons is badly needed.* We note, in addition, that the presence of gamma rays in primary cosmic rays has not yet been reliably established, nor have any antiprotons or antinuclei been observed.

b) Energy Spectrum. Isotropy of Cosmic Rays

The flux of cosmic rays with kinetic energies E_k greater than 1 Bev/nucleon diminishes monotonically and rather rapidly with increasing energy (Fig. 4). If we denote by $F_A(>\epsilon)$ the flux of particles with atomic weight A and total energy† (per nucleon) greater than ϵ, then the energy spectrum can be approximately represented in the form

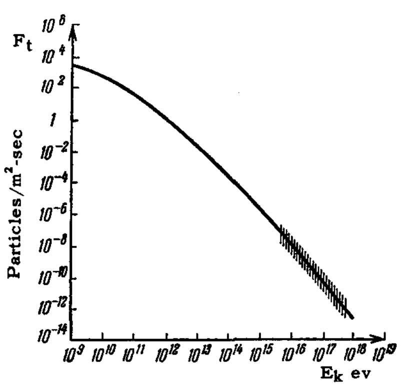


FIG. 4. Total flux of all cosmic rays $F_t = \pi F$ [number per m²-sec, of particles with kinetic energy greater than E_k(ev)]. The hatched region characterizes the possible measurement inaccuracy.

*Note added in proof. This problem has by now been solved in principle. In a communication by J. A. Earl, Physical Review Letter 6, 125 (1960), published after this article was written, it is reported that light particles (electrons and positrons, which could not be distinguished from each other) have been observed in primary cosmic rays. According to preliminary data, the flux of electrons with energy $E \gtrsim 1.5$ Bev amounted in this case to about 1% to the proton flux. This agrees with the assumed approximate ratio, 1%, used for the same fluxes in the present article.

†The total energy of a particle with mass M is $E = E_k + Mc^2 = A\varepsilon_k + AM_pc^2$, where M_p is the proton mass (we neglect the mass difference between the proton and neutron). Obviously, $\varepsilon = \varepsilon_k + 0.938$ Bev, since $M_pc^2 = 0.938$ Bev for a proton.

$$F_A(>\varepsilon) = \frac{K_A}{\varepsilon^{\gamma-1}}, \tag{2}$$

where for protons and all the nuclei we have $\gamma = 2.5 \pm 0.2$. The spectrum (2) is called the integral spectrum; the differential spectrum is $F_A(\epsilon) = (\gamma-1)K_A\epsilon^{-\gamma}$, inasmuch as $F_A(>\epsilon) = \int_\epsilon^\infty F_A(\epsilon)\,d\epsilon$. For protons $K_p \simeq 4{,}000$ (the energy ϵ amounts to several Bev). Therefore, according to the data of Table I, we have F_p (> 2.5 Bev) ≃ 1300 protons/m² sr-sec. As already indicated, the total flux is $F_t = \pi F$, and consequently, the earth receives some 4,000 protons per square meter per second.* The flux of all the other particles can also be readily obtained with the aid of (2) and Table I.

Particular interest is attached to the energy spectrum of cosmic rays in the region of low and high energies. Thus, for relatively "soft" particles with kinetic energy $\epsilon_k \lesssim 1$ Bev/nucleon, the spectrum is no longer given by (2). Qualitatively, the difference lies in the fact that the flux no longer increases with decreasing energy. This means that the curve (integral spectrum) $F(>\epsilon)$ reaches "saturation" (becomes horizontal), and the $F(\epsilon)$ curve (differential spectrum) has a maximum at some energy $\epsilon_{k,max} < 1$ Bev/nucleon. This effect—the absence of low-energy particles in the primary cosmic rays on earth—is called the high-latitude spectrum cutoff (particles with $\epsilon_k < 1$ Bev/nucleon can reach the earth only at sufficiently high latitudes). The value of the energy $\epsilon_{k,max}$, and the entire character of the high-latitude spectrum cutoff, depend on the solar-activity cycle. During the minimum of solar activity (the last minimum was observed in 1954, and the next is expected in 1965) the high-latitude cutoff is apparently weakly pronounced or perhaps completely lacking. To the contrary, during high solar activity, when there are many sunspots, or when the sun ejects gas streams etc., the high-latitude cutoff is most clearly pronounced. This circumstance, in spite of the incompleteness of the available data, gives grounds for assuming that the high-latitude cutoff is due to magnetic fields in the solar system. Such fields are "frozen-in" in the streams of ionized gas ejected from the sun. Nor is it excluded that the solar system contains also a quasi-regular magnetic field, produced by currents flowing in the plane of the earth's orbit in the interplanetary gas.

In addition to the high-latitude cutoff, the existence of a magnetic field in the solar system leads to variations of the intensity of the cosmic rays. These variations depend on the latitude and on the height of the point of observation above sea level; on the whole,

*Particles with $\varepsilon = 2.5$ Bev can reach the earth only at sufficiently high latitudes. Only protons with $\varepsilon > 15$ Bev reach the equator in a vertical direction. Their total flux is $F_t \simeq 220$ protons/m² sec.

they are determined by the solar activity. It has also been established that the sun sometimes (during the last two or three years—approximately once a month) emits cosmic rays with an essentially relatively low kinetic energy ϵ_k, less than $(1-3) \times 10^8$ ev. Such particles arrive only at high latitudes and were observed with the aid of pilot balloons and satellites. During the past twenty years, several powerful "flares" of solar cosmic rays have also been recorded. The greatest of these occurred on February 23, 1956. During the time of this flare, the flux of cosmic rays increased by a factor of several times even on the earth's surface. For example, in Moscow the flux increased four times; two hours after the start of the flare, the increase in the flux was already 20%. During the powerful flares registered at other times, the flux on the earth increased by at most several times 10%.

A study of the solar cosmic rays and of the influence of solar activity on the cosmic rays arriving from the galaxy is now an independent field of research, closely connected with the physics of the sun and of the interplanetary medium.

While "soft" cosmic rays yield information on the sun and solar streams, a study of the "hardest" particles of cosmic radiation is particularly important for the clarification of the role of cosmic rays of extragalactic origin. Unfortunately, an investigation of cosmic rays of very high energy is very difficult, and relatively little has been obtained as yet. The primary reason is that the flux of high-energy particles is very small. Actually, if we use for the flux of all the cosmic rays expression (2), with K = 5,000 and $\gamma = 2.5$, and if we substitute for ϵ the total energy E of the particle, then the fluxes of particles with energy E greater than 10^{15}, 10^{17}, and 10^{19} ev (i.e., 10^6, 10^8, and 10^{10} Bev) are respectively

$$\left.\begin{aligned} &F(E > 10^6\,\text{Bev}) = 5\cdot 10^{-6}, \quad F(E > 10^8\,\text{Bev}) = 5\cdot 10^{-9}, \\ &F(E > 10^{10}\,\text{Bev}) = 5\cdot 10^{-12}\cdot\frac{\text{particle}}{\text{m}^2\,\text{sr-sec}}. \end{aligned}\right\} \quad (3)$$

A year has approximately 3×10^7 sec and a particle with energy greater than 10^{19} should fall on a square meter of the earth's surface (from all directions) on the average once every 2,000 years! Actually the flux of particles with very high energy is even much less, because the power law (2) is valid only in a limited energy interval, and the spectrum falls off with increasing energy more steeply than called for by (2) with $\gamma = 2.5$ (according to some data, in the energy region $E > 5 \times 10^{15}$ ev the exponent γ amounts to 3.17 ± 0.10; see also Fig. 4).

In spite of this, particles of energy up to 10^{19} ev have been observed. This was made possible by observation of extensive air showers. The method of extensive air showers is the only one used in the investigation of cosmic rays of energy greater than $10^{14} - 10^{15}$ ev. The mechanism of formation of extensive showers is as follows: After falling into the atmosphere, the high-energy proton or nucleus collides in air with the nitrogen or oxygen nuclei, producing a whole series of high-energy particles (nucleons from the nitrogen and oxygen nuclei, nucleon-antinucleon pairs, hyperons, K mesons and π mesons). All these particles in turn disintegrate other nuclei or break up into other particles (for example, the decays $\pi^\pm \rightarrow \mu^\pm + \nu$ or $\mu^\pm \rightarrow e^\pm + \nu + \bar{\nu}$ take place).* Such a cascade produces in the atmosphere an extensive shower containing a tremendous number of particles (near the earth's surface these particles are essentially electrons, positrons, and protons). The area of the shower depends on the energy of the primary particle and can reach many square kilometers. The shower is observed and investigated with a system of various types of counters, arranged over a large area and connected "for coincidence." The system employed makes it possible to register the particles which fall on a large area, and such an event is not so rare. Thus, for example, a particle of energy $E > 10^{19}$ ev will fall on an area of 10 km^2 once every several days.

Thus, the observation of extensive showers makes it possible to register such rare events as the arrival of particles with energies $10^{18} - 10^{19}$ ev. But the "cost" of this is quite high. First, the determination of the energy of the primary particles is not very accurate. Second, and most important, it is impossible to ascertain which particle produces the shower—a proton or some other nucleus. Therefore, when cosmic rays are investigated by showers only, we do not know their chemical composition. We note that if this composition is the same as of low-energy cosmic rays, then somewhat more than half of all the showers with total energy greater than specified is produced by nuclei and not by protons. It is not excluded that all particles with energy greater than, say, 10^{17} ev are iron or chromium nuclei. Then the energy per nucleon is some 50 times smaller than the total particle energy. This is very important for an explanation of the origin of the particle with the highest energy. The point is that the radius of curvature of the trajectory of a proton with energy 10^{19} ev in a field 10^{-5} oe is 3×10^{21} cm, i.e., it is already comparable with the radius of the galaxy, $(3-5) \times 10^{22}$ cm. An iron nucleus with the same total energy has a radius of curvature Z (= 26) times smaller, i.e., approximately 10^{20} cm. Such a nucleus can probably still be retained in our galaxy and be of galactic origin, while protons with energy $E > 3 \times 10^{18} - 10^{19}$ ev apparently cannot be retained in the galaxy and must have been produced outside it.

Cosmic rays formed outside the galaxy are usually called metagalactic. They could, in principle, be accelerated in other galaxies or in metagalactic (inter-

*Here, as usual, the pion, muon, electron, and neutrino are designated by the letters π, μ, e, and ν; $\bar{\nu}$ is the antineutrino, and the $\pm$ signs indicate the particle charges.

galactic) space. It is not yet clear whether the radius of curvature of the particles with highest observed energy is comparable with the dimensions of the galaxy, or whether it is considerably less. For the bulk of the cosmic rays this radius is undoubtedly negligible even compared with the distance to the nearest stars. Thus, as already mentioned, at an energy of 10^{10} ev in a field of 10^{-6} oe, the radius of curvature of the proton trajectory is 3×10^{13} cm, whereas the distance to the nearest star from the earth is approximately four light years, i.e., about 4×10^{18} cm.

It is precisely the smallness of the radius of curvature of the cosmic rays, and also the irregularity and the "entanglement" of the interstellar magnetic field, that ensure the isotropy of cosmic radiation. Qualitatively the degree of anisotropy is characterized by a coefficient $\delta = (F_{max} - F_{min})/(F_{max} + F_{min})$, where F_{max} and F_{min} are the maximum and minimum fluxes of cosmic rays beyond the influence of the earth's magnetic field. The values of the flux away from the earth can be estimated from measurements near the earth, since the character of motion of the particles in the earth's magnetic field is known. We recall also that F is the flux in any direction, and consequently, for example, F_{max} represents the flux in the direction in which the value of F is a maximum. From the available data, the coefficient δ is less than 1% for particles with energy $E < 10^{16}$ ev. At still higher energies, the measurement accuracy is lower, but no anisotropy of the primary cosmic rays has been observed within the limits of the accuracy attained. It is quite possible that more careful observations will disclose a small anisotropy ($\delta < 1\%$) both for the main fraction of cosmic rays,* and perhaps also for particles with very high energy.

2. RADIO ASTRONOMY AND COSMIC RAYS

Until recently practically the only source of information on the cosmos was visible radiation from the sun, stars, the galaxy, etc. At present, the investigation of cosmic radio emission has become a method of equal importance; this research comprises the main purpose of radio astronomy. Cosmic radio emission arriving from our galaxy was observed in 1931 — 1932. The radio emission from the sun was first observed in 1942 — 1943. Until 1945, however, the number of radio astronomic investigations was very small, and only in subsequent years did radio astronomy start to develop vigorously. This has led to discoveries of great importance. Radio methods are now used on par with optical ones, and studies of the most important problems (for example, solar physics) are carried out simultaneously by both methods. The division of astronomy into optical astronomy and radio astronomy becomes therefore more and more a division of methodological character, and does not concern the nature of the investigated problems. It is remarkable that within the some 15 years of its development, radio astronomy has reached almost the same status as optical astronomy, which dates back from antiquity.

*Certain indications of the presence of such an anisotropy during the minimum of solar activity have been recently obtained. This effect is connected with the fact that cosmic rays are formed essentially in the central regions of the galaxy (see Sec. 3).

From the point of view of further discussions, only two aspects of radio astronomy are of importance to us. These are the nature of cosmic radio emission and the "radio map of the sky."

a) Nature of Cosmic Radio Emission and Cosmic Rays

All the received cosmic radio emission can be divided into three components: thermal radiation with continuous spectrum, thermal radiation of neutral hydrogen at approximate wavelength 21 cm, and nonthermal cosmic radio emission. The first of these components is by its nature electron bremsstrahlung produced when the electrons collide with ions in the interstellar medium. The intensity of this radiation is, naturally, particularly large in regions where the gas temperature and the degree of ionization are high. This occurs, for example, near especially hot stars. Certain regions of the atmosphere of various stars, including some that are not very hot, are also highly heated. Our own sun is a star of this type. The corresponding stellar-atmosphere radio emission can be received only from the sun. When we speak later on of cosmic radio emission, we shall refer only to radiation produced outside the solar system.

The temperature of the ionized gas in our own galaxy does not exceed 10,000°, and the maximum temperature of the thermal radio emission from this gas has the same value.*

Monochromatic cosmic radio emission of neutral hydrogen ($\lambda = 21$ cm), observed in 1951, is also essentially thermal (equlibrium) radiation, its temperature not exceeding about 100° K. The radiation on 21 cm is emitted via transitions between the sublevels of hyperfine structure of the ground level of the hydrogen atom. Two sublevels of the hyperfine structure of hydrogen correspond to two possible relative spin orientations of the electron and proton of the hydrogen atom.

Before this method was developed, i.e., prior to the reception of the 21-cm spectral line, information could be gained only on light-emitting excited hydrogen atoms. Naturally, there are much fewer such excited atoms than there are unexcited ones. Furthermore,

*The intensity I_ν of thermal radiation from a medium of temperature T is equal to

$$I_\nu = \frac{2k\nu^2}{c^2} T_{eff}, \quad T_{eff} = T(1 - e^{-\tau}), \tag{4}$$

where $\nu = c/\lambda$ is the radiation frequency and τ is the optical thickness of the medium; $h\nu \ll kT$ (h is Planck's constant, and $k = 1.38 \times 10^{-16}$ erg/deg is Boltzmann's constant). It is clear from (4) that the effective temperature T_{eff} is less than or equal to T.

the number of excited atoms is so small in many regions that their light cannot be noted. In addition, radiation in the form of light is strongly scattered and absorbed in the interstellar (cosmic) dust. Radio waves are incomparably less scattered and absorbed by the dust. Reception of radio waves on 21 cm is therefore of vital importance to astronomy, and has made it possible for the first time to investigate with sufficient detail the spiral structure in the central regions of our galaxy.

For our topic, the most interesting is the third component of cosmic radio emission—the nonthermal radiation with continuous spectrum. This radiation arrives from all directions in the galaxy, from separate nebulae in the galaxy, and from other galaxies. It can be quite readily established that by far not all cosmic radio emission is thermal. This is seen directly from the fact that the radiation received at wavelengths longer than several meters has a very high intensity. Thus, the effective temperature* of cosmic radio emission on 16 meters reaches 3×10^5 deg K, while on 30 meters it already reaches 10^6 deg K. Yet, as already noted, the effective temperature of the thermal radiation of interstellar gas cannot exceed the temperature of this gas, i.e., approximately 10^4 degrees.

Consequently, there certainly exists some powerful nonthermal cosmic radio emission. Moreover, it is precisely this emission that makes up in most cases the dominating part of the cosmic radio emission.

What is the nature of this nonthermal cosmic radio emission?

It was not easy to find the answer to this question. For a long time attempts were made to assume that the nonthermal radio emission is generated in shells of a tremendous number of hypothetical radio stars, which have unusual properties and which cannot be observed in the optical region of the spectrum. Inasmuch as this assumption has now been set aside, there is no point in discussing it in detail.

Another explanation of the origin of nonthermal cosmic radio emission was proposed and developed in 1950 — 1953 and proved to be correct. It amounts to stating that the nonthermal cosmic radio emission is magnetic bremsstrahlung (synchrotron) radiation of the relativistic electrons that make up the electronic component of the cosmic rays.

By the same token, a remarkable connection has been established between the radio emission and the cosmic rays: the main part of the cosmic radio emission is generated by the cosmic rays!

This is precisely why radio astronomy gives us the key to the investigation of the cosmic rays in the universe, and brings us close to the solution of the problem of the origin of cosmic rays. It is curious to note that the magnetic bremsstrahlung theory of cosmic radio emission was not immediately universally accepted. It is sufficient to say that a paper devoted to this theory, delivered by the author of this article to the 1955 Manchester Symposium on Radio Astronomy, was not even published in the proceedings of the symposium. At the same time the same proceedings, which were published in 1957, contained an article in which the nonthermal radio emission was connected with the hypothesis of existence of radio stars.

Before proceeding to discussing the results of the radio-astronomical research, let us stop to discuss the singularities of the magnetic bremsstrahlung mechanism of radiation.

A charged particle moving in a magnetic field of intensity H, as in the case of any uniform motion, emits electromagnetic waves. The cyclic frequency of the radiated waves, ω, is equal to the angular frequency of rotation of the particle in a magnetic field ω_H^* and to its overtones $n\omega_H^*$, where n is any integer. Let us consider, to be specific, an electron; we then have

$$\omega_H^* = \frac{eH}{mc}\,\frac{mc^2}{E} = 1.76 \cdot H\,\frac{mc^2}{E}\,, \tag{5}$$

where E is the total electron energy and $mc^2 = 5.1 \times 10^5$ ev is its rest mass.

A nonrelativistic electron [for which $(E - mc^2) \ll mc^2$] emits practically only the fundamental frequency $\omega_H^* \simeq \omega_H = eH/mc$; this radiation is similar in character to the radiation from two mutually perpendicular dipoles, whose phases are shifted 90°. In the ultrarelativistic case of interest to us, when $E \gg mc^2$, the particle radiates predominantly in the direction of its instantaneous velocity—the radiation is concentrated in a narrow cone with angle $\theta \sim mc^2/E \ll 1$. Therefore, if the electron moves in a circle (this occurs when its velocity v is perpendicular to the field H), the electromagnetic waves are emitted the way sparks are produced when a knife is placed against a rotating emery wheel. In other words, an observer located in the plane of the orbit will observe radiation flashes, following one another at time intervals $\tau = 2\pi/\omega_H^*$ (Fig. 5). The duration of each flash, as can be shown, has an order of magnitude $\Delta\tau \sim (r\theta/c)(mc^2/E)^2 \sim (mc/eH)(mc^2/E)^2$, where $r = c/\omega_H^*$ is the radius of the orbit, and the factor $(mc^2/E)^2$ is brought about by the Doppler effect. Inasmuch as the radiation is periodic in character (the period is $\tau = 2\pi/\omega_H^*$) its frequency spectrum, as already mentioned, will consist of the overtones of the frequency ω_H^*. The frequencies with maximum intensity will be of the order $1/\Delta\tau \sim \omega_m = (eH/mc)(E/mc^2)^2$, corresponding to the characteristic duration of the flashes $\Delta\tau$. For an electron with energy E, say, equal to 5×10^8 in a field $H = 10^{-5}$ oe, we have $\omega_H^* = 0.176$ and $\omega_m \sim 10^8$; consequently, the very high overtones $\omega_m = n_m\omega_H$ are represented in the spectrum, with $n \sim 10^9$ in our example. Under these conditions, evi-

*The intensity I_ν of any radio emission at a given frequency ν can be characterized by an effective temperature T_{eff}, determined from the formula $I_\nu = (2k\nu^2/c^2)\,T_{eff} \equiv (2k/\lambda^2)\,T_{eff}$.

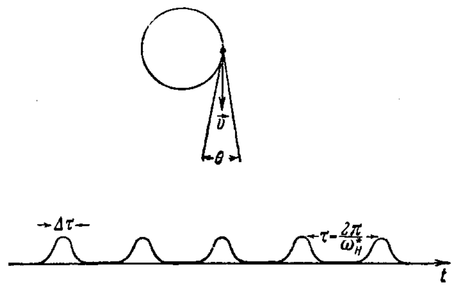


FIG. 5. Magnetic bremsstrahlung (synchrotron) radiation [the particle moves along a circle with velocity v ($v \simeq c$)] and angular velocity

$$\omega_H^* = \frac{eH}{mc}\frac{mc^2}{E}.$$

In the lower part of the figure is plotted the intensity of radiation, that would be registered by an instrument located in the plane of the orbit of the particle.

dently, the spectrum is so "dense" that it appears to be almost continuous (Fig. 6).

The energy $P(\nu, E)\,d\nu$ radiated by the electron per second in the frequency interval $d\nu = d\omega/2\pi$ is

$$P(\nu, E) = 16\frac{e^3H_\perp}{mc^2}\,p\left(\frac{\omega}{\omega_m}\right), \quad \omega_m = \frac{eH_\perp}{mc}\left(\frac{E}{mc^2}\right)^2; \qquad (6)$$

The function $p(\omega/\omega_m)$ is plotted in Fig. 6.

Corresponding to the maximum of radiation is a frequency ν_{max} and an energy $P(\nu_{max}, E)$, equal to

$$\nu_{max} = 0.5\frac{\omega_m}{2\pi} = 1.4\cdot 10^6 H_\perp\left(\frac{E}{mc^2}\right)^2 \text{ cps},$$

$$P(\nu_{max}, E) = 1.6\frac{e^3H_\perp}{mc^2} = 2.16\cdot 10^{-22}H_\perp \text{ erg/sec-cps}. \qquad (7)$$

We note that the field H has been replaced in (6) and (7) by $H_\perp$ —the projection of H on a plane perpendicular to the particle velocity **v**, since it is precisely $H_\perp$ that is involved in the formulas for the general case of helical motion of a particle.

It has been established that magnetic fields with intensity $H \sim 10^{-6} - 10^{-5}$ oe exist in interstellar space. If $H_\perp \sim 3 \times 10^{-6}$ oe and $E \sim 5 \times 10^9$ ev, then $\nu_{max} \sim 4 \times 10^8$ and the wavelength is $\lambda_{max} = c/\nu_{max} \sim 0.7$ m It is clear even from this example that the cosmic-ray electrons, with energies $10^8 - 10^{10}$ ev, will produce in interstellar space magnetic bremsstrahlung in the radio band. As regards the intensity of the radio emission, simple estimates by means of formula (7) show that to

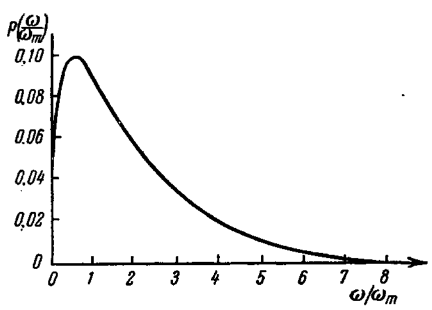


FIG. 6. Magnetic bremsstrahlung spectrum.

explain the observed nonthermal radio emission in the interstellar space it is sufficient that the flux of electrons with energy greater than 10^9 ev, $F_e\,(E > 10^9$ ev), have in the galaxy a value on the order of 10 electrons/m^2 sr-sec. This is only a fraction of one percent of the flux of all the cosmic rays on earth, and consequently does not contradict the available data on the flux of electrons and positrons near the earth.

We note that the magnetic bremsstrahlung is almost completely polarized in a way that the electric vector in the wave is perpendicular to the magnetic field and to the particle velocity vector. But the galactic radio emission observed in the meter band is practically unpolarized. This is caused by two factors. First, the magnetic field will have different orientations in different places along a line of sight through the galaxy, so that the total radiation will naturally be depolarized to a considerable extent. Second, the magnetic field in the interstellar medium causes the plane of polarization of the radio waves to be rotated,* and this again depolarizes the radio emission. As a result, the cosmic magnetic bremsstrahlung is polarized to any noticeable extent only in exceptional cases, which will be noted later (most recently, the galactic radio emission on 73 cm was found to be polarized for certain directions).

The spectrum of the electrons in outer space, at least in a limited energy interval, can be assumed to obey a power law. This means that the concentration of electrons with energies from E to E + dE is equal to N(E)dE, with

$$N_e(E) = \frac{K_e}{E^\gamma}. \qquad (8)$$

For relativistic particles, as already indicated, the fluxes are $F(E) = cN(E)/4\pi$ and $F(>E) = \int_E^\infty F(E)\,dE$. Therefore, the flux of electrons having a spectrum (8) is equal to $F_e(>E) = cK_e/4\pi(\gamma - 1)E^{\gamma-1}$. For cosmic electrons with spectrum (8), the intensity of radio emission has the form

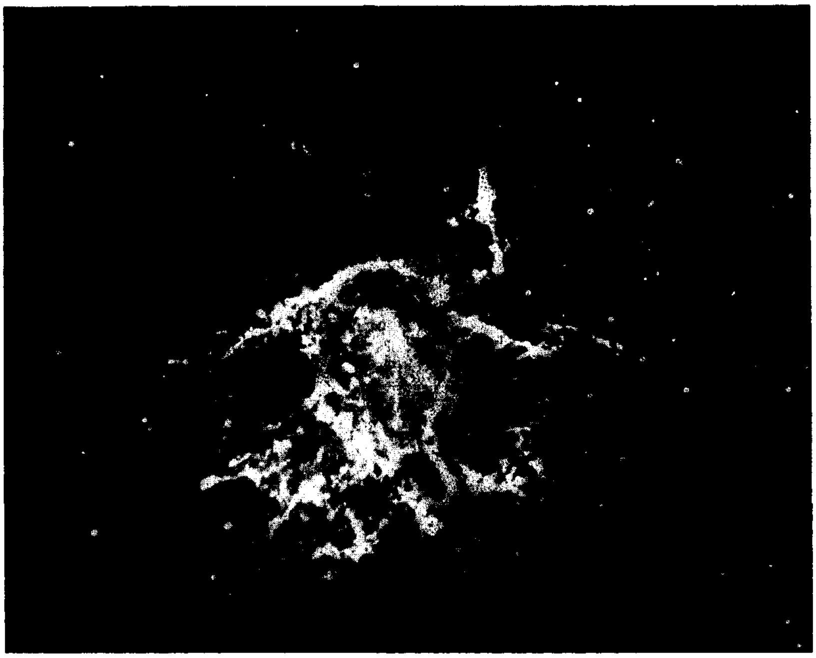
$$I_\nu \equiv \frac{2k\nu^2}{c^2}T_{\text{eff}} = f(\gamma)K_eRH_\perp^{\frac{\gamma+1}{2}}\nu^{-\frac{\gamma-1}{2}}, \qquad (9)$$

where $f(\gamma)$ is a certain function of γ, R is the extent of the radiating region along the line of sight, and $H_\perp$ is the average value of the perpendicular component of the field along the line of sight; for example, with $\gamma = 3$, we have $f(\gamma) = 170$, and I_ν is measured in erg/cm^2 sr-sec-cps = 10^{-3} w/m^2 sr-cps.

By determining from observations the dependence of the intensity of the radio emission I_ν on the fre-

*The effect of rotation of the plane of polarization in a very weak field is noticeable in the case of a rarefied medium because of the tremendous space over which interstellar fields extend. We note that the magnetic bremsstrahlung itself in the interstellar medium can be usually assumed to be the same as produced by an electron moving in vacuum, since the refractive index of the medium is in this case very close to unity.

a)



b)

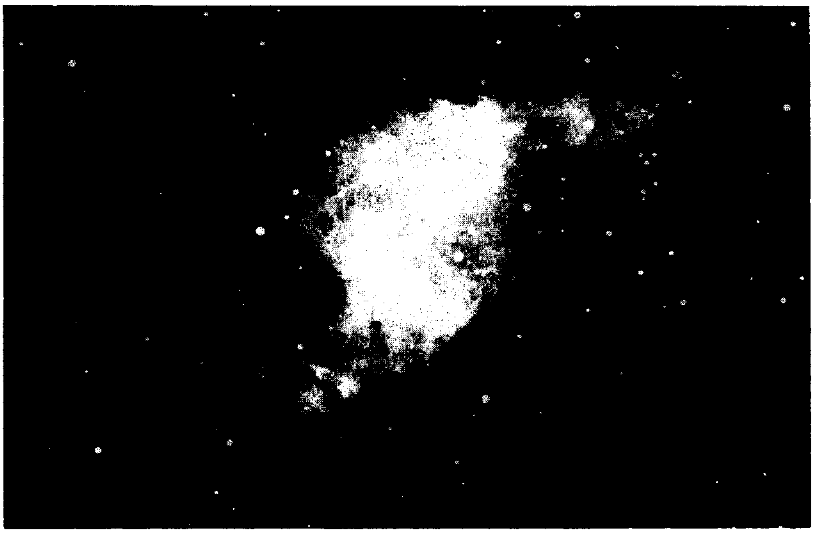


FIG. 7. Crab nebula (source A Tauri). a) Photograph in rays of a strong spectral line; b) photograph in continuous spectrum.

quency ν, we obtain directly the exponent of the electron energy spectrum. From the quantity I_ν itself we can determine the product $K_e R H_\perp^{(\gamma+1)/2}$, and then estimate K_e, since the values of R and $H_\perp$ are usually known, albeit roughly. Consequently, from the intensity of the cosmic radio emission and from its dependence on the frequency and on the direction of observation we can gain information on the electronic component of cosmic rays both in our own galaxy and in very distant galaxies.

b) Cosmic Rays in the Universe

We are familiar with maps of the sky and with photographs of individual regions of the milky way or nebulae, made with the aid of optical telescopes. All these photographs and maps show the distribution in the universe of the brightest stars, stellar clusters inside galactic nebulae, and galaxies. But even the optical map of the sky is different when photographed with different optical filters, i.e., at different wavelengths. By way of example, Fig. 7 shows photographs of the famous Crab nebula in the Taurus constellation, taken with the rays of one of the strong spectral lines and with a continuous spectrum (in this case an optical filter that does not transmit the strong spectral lines is used). If the photographs are taken not in visible light, but in the infrared or ultraviolet, the map of the sky will, naturally, change even more than on going from red to violet rays.

At radio wavelengths, the sky is no longer recognizable. To be sure, we do not possess "radio vision" in the literal sense of this word, but we can see the sky in radio waves on an oscillograph screen. In prac-

FIG. 8. The galaxy NGC 4565 (NGC – New General Catalog, 4565 – number of object in this catalog). The dark strip in the center of the disk is due to absorption of light by cosmic dust, concentrated in the galactic plane.

tice, naturally, radio maps of the sky are constructed or are simply drawn from measurements of the intensity of radio emission in different directions.

On the "optical sky," the sun occupies an exclusive position—even the moon radiates 10^6 times less light. On the "radio sky," in the meter wave band, we have three suns—three particularly bright sources. One is the sun, the other the radio source of A Cassiopeiae, and the third source A Cygni.* It is intersting that the last two powerful discrete cosmic radio emission sources cannot be noted on ordinary photographs made even with good telescopes. Only special photographs on the largest existing telescope (five meters in diameter) made it possible in 1951 to observe in the location of A Cassiopeiae the shell of a supernova, and a remote galaxy in the location of A Cygni.

Among the weaker radio sources is the Crab nebula (radio source A Tauri), from which the radio emission flux on three meters is 12 times smaller than from A Cassiopeiae and seven times smaller than from A Cygni.

The difference between the optical and radio maps of the sky becomes even clearer, if it is pointed out that no radio emission has been observed from any of the bright stars. Finally, in spite of the presence on the radio sky of many discrete sources, it is the entire sky that "glows" brightly at the meter and longer wavelengths. This is the origin of the term "discrete sources" of cosmic radio emission, as a contrast with sources continuously distributed in all directions. It was already pointed out that at 16 meters the effective temperature of the continuous, or as it is more frequently, called overall radio emission of the galaxy is on the order of 10^5 deg.†

What is the appearance of the galaxy as seen with radio waves? Before answering this question, let us recall the appearance of our optical galaxy. Naturally, we cannot obtain a photograph of the entire galaxy while we are inside it. We shall therefore show photographs of two spiral galaxies, one seen from the earth sideways, and the other "from above" (Figs. 8 and 9). Our own galaxy, which is also spiral, contains approximately 100 billion stars, the brightest of which form the denser disk at the center. Galaxies usually rotate rather rapidly. Thus, the sun which is 25,000 light years away from the center of the galaxy, makes one revolution about the center in approximately 220 million years; the speed of the solar system, due to its motion around the center, is approximately 200 km/sec. The arms of the galactic spiral, in which the young stars and the interstellar gas are concentrated, are not at all regular or continuous. This is particularly clear from data on the distribution of neutral hydrogen in the galaxy, obtained on 21 cm. On the basis of these data one can trace the picture shown in Fig. 10, on which the clusters of hydrogen in the arms are represented in the form of bright strips, the galactic center is marked with a cross, and the solar system is marked by the dot with surrounding circle; the region near the line from the sun to the center cannot be investigated and consequently the hydrogen clusters are not shown here. From Fig. 10 and from a more detailed analysis it follows that the arms of the spiral are not solid, but consist of several pieces which are inhomogeneous in length and in thickness;* in addition, the arms are formed only at a distance of about 9,000 light years from the center.

*Let us point out that a difference exists between these two sources when observed at radio frequencies. The angular dimension of the sun in the meter band is 40 – 50 angular minutes. The sources A Cassiopeiae and A Cygni are only several angular minutes in size. In addition, the position of the sun on the sky varies, owing to the earth's annual motion. Finally, the intensity of the solar radio emission in the meter band is sometimes highly variable, as a result of sunspots, flares, etc.

†According to (4), $T_{eff} = c^2 I_\nu / 2k\nu^2$, and for magnetic bremsstrahlung I_ν is proportional to $\nu^{-\alpha}$, where $\alpha = (\gamma - 1)/2$ [see (9)]. For the overall galactic radio emission, some measurements yield $\alpha \sim 0.7$, i.e., T_{eff} is proportional to $\nu^{-2.7}$. Such a rapid decrease in T_{eff} with increasing frequency is evidence, on the one hand, of the nonthermal character of the radiation. On the other hand, this explains why the total energy of the cosmic radio emission reaching the earch is relatively low. Obviously, life on earth would be impossible even were the radiation temperature T_{eff} to be approximately 400°K and constant up to infrared rays.

*A quasi-ordered magnetic field $H \sim 10^{-5}$ oe exists in the arms, with preferred orientation along the arm. Thus the arms form so to speak force tubes of magnetic field lines; this field undoubtedly plays an important role in their formation. The fact that the arms do not form a regular spiral becomes understandable if it is recalled that the galaxy rotates. During the time that the galaxy has existed in a state close to its present one (approximately 10 billion years), for example, the solar system has made 25 revolutions about the galactic center and it is clear that the force tubes could not remain unbroken.

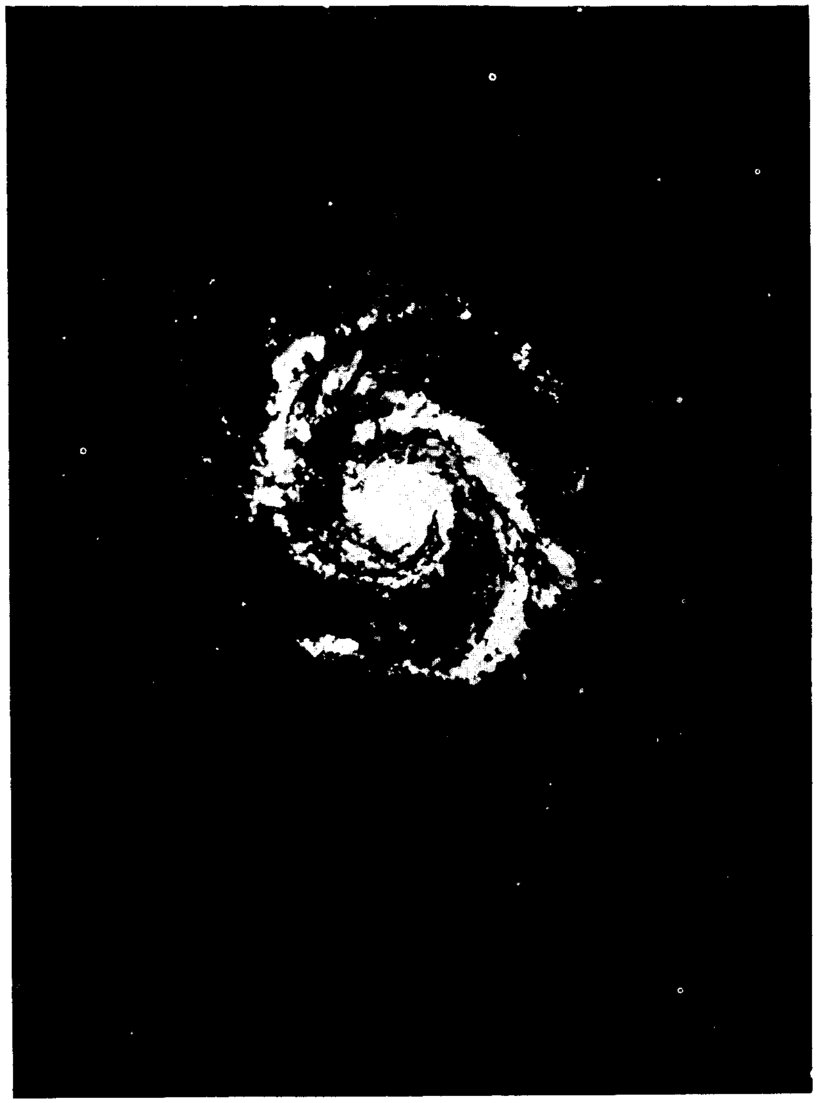


FIG. 9. Galaxy NCG 5194.

We note that, owing to the interstellar absorption of light, it is impossible to make any detailed study of the spiral structure in the central regions of the galaxy by means of optical astronomy; with the development of radio astronomy, important results in this direction have been immediately obtained. In particular, the existence of a galactic center, measuring about 30 light years, has been observed. The core contains ionized hydrogen with an average concentration $\bar{n}$ on the order of 10^3 cm^{-3}, which is several thousand times greater than the average concentration of hydrogen in the galactic plane. The core is a source of thermal radio emission, and is surrounded by a no less interesting region of neutral hydrogen with a radius of approximately 1,000 light years. Here $\bar{n} \sim 1-2$, and therefore this entire mass of hydrogen rapidly rotates about the galactic core, more accurately about a certain center which apparently coincides with the center of the core. The central portion of the galaxy is also a source of more intense nonthermal radio emission, compared with the adjacent regions. This is explained perhaps not by the increase in the amount of cosmic rays, but the strengthening of the magnetic field in this region; it is clear from formula (9) that, for example, when $\gamma = 2.4$, the intensity of the radio emission is proportional to $H_{\perp}^{1.7}$.

We have actually embarked on a description of the picture of the sky as seen in the meter radio band. Two elements of this picture are the aforementioned galactic core (source of thermal radio emission) and the central radio region—source of increased intensity of magnetic bremsstrahlung. Roughly speaking, this source has the shape of an ellipsoid of revolution with axes of about 1,000 and 4,000 light years; see Fig. 11. The third element of the picture is the radio disk of the galaxy—a region approximately 1500 light years thick, which encompasses the optical disk of the galaxy with its spiral structure (the thickness of the arms of the optical spiral is about 750 light years). Finally, the last element is the galactic halo or corona—an almost spherical region, including the entire visible galaxy. About 90% of the total general galactic radio emis-

FIG. 10. Clusters of neutral hydrogen in the galaxy.

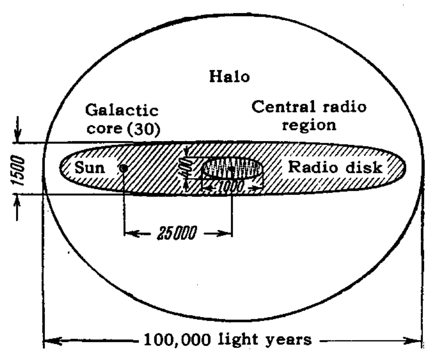


FIG. 11. Schematic representation of the galaxy as seen in radio waves in the meter band (the scales on the figure are not consistent; all dimensions are shown in light years and are tentative.

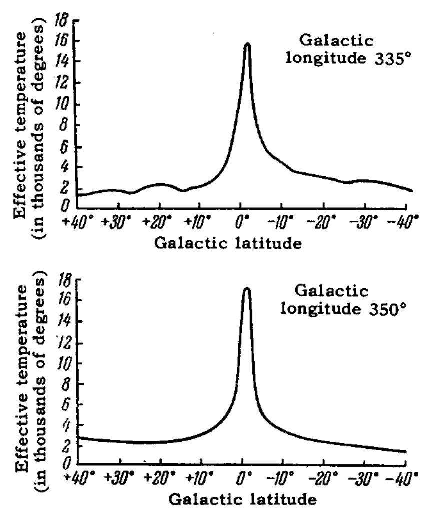


FIG. 12. Effective temperature of galactic radio emission on 3.5 meters.

sion comes from this region, which has a radius of approximately 30 — 50 thousand light years. Between the radio disk and the halo there is apparently no clear cut boundary, merely an increase, as it were, of the radio brightness of the halo as the galactic plane is approached. Figure 12 shows the results of measurements of the effective temperature of the cosmic radio emission on 3.5 meters as a function of the galactic latitude, for two galactic longitudes. (We recall that the galactic latitude is reckoned from the plane of the galaxy, which is at 0° latitude. The galactic longitude determines the position of the line of sight in the galactic plane.)

Thus, when viewed in radio rays, the galaxy is far from being a relatively thin disk bulging at the center. To the contrary, it recalls a sphere or a slightly oblate ellipsoid. The same pertains to most other galaxies, particularly the great nebula in the Andromeda constellation, the spiral galaxy closest to us. The proof of existence of galactic halos, obtained by radio observations, is one of the greatest accomplishments of astronomy during the past decade. This fact is of particular importance to our subject, since the radio emission from the halo is due to the presence of relativistic electrons and cosmic rays in general, as well as magnetic fields, in these gigantic galactic shells. In addition, the halo contains highly rarefied ionized gas (average concentration $\bar{n} \sim 10^{-2}$ cm^{-3}, or even less), in which the magnetic fields are "frozen in." The very existence of the halo is apparently closely connected with the cosmic rays. The cosmic rays produced in the central radio region and in the radio disk emerge from these regions and drag with them the magnetic fields and the gas. The point is that the cosmic rays are quite securely "tied" to the force lines of the field, and this field itself is dragged by the gas in which the currents producing this field flow. Naturally, such an interrelationship between the cosmic rays, the field, and the motion of the gas masses will be close and indeed reciprocal only if the energies of all these "inhabitants" of the interstellar space are commensurate with each other. And this is precisely the case!

In fact, the concentration of cosmic rays on earth is $N = 4\pi F/c \sim 10^{-10}$ cm^{-3}, and the average energy density is $w = N\bar{E} \sim 1$ ev/cm^3 (average energy $\bar{E} \sim 10^{10}$ ev, 1 ev = 1.6×10^{-12} erg). On the average the energy density w in the halo is probably only a few times smaller, say, 0.3 ev/cm^3. At the same time the energy density of the magnetic field, $H^2/8\pi$, is on the order of 0.3 ev/cm^3 for a field $H \sim 4 \times 10^{-6}$ oe. But precisely such fields exist in the galaxy [in the spiral, probably, $H \simeq 10^{-5}$ oe, and on the periphery of the halo $H \simeq (1-3) \times 10^{-6}$ oe]. Finally, the average density of the interstellar gas at an average concentration $n \sim 10^{-2}$ cm^{-3} is on the order of $\bar{\rho} \sim 2 \times 10^{-26}$ g/cm^3 (the gas is 90% hydrogen, and the mass of a hydrogen atom is 1.67×10^{-24} g). Hence the kinetic energy density of the gas $\bar{\rho}v^2/2$ is on the order of 0.3 ev/cm^3 at a velocity $v \sim 7 \times 10^6$ cm/sec. The observed random velocities of the gas masses in the galaxy are usually several times smaller, but on the other hand the density in the observed gas clouds is appreciably higher than that assumed.

It is clear even from this that the cosmic rays in our galaxy are not a byproduct or a secondary phenomenon. To the contrary, their action belongs to those factors that determine the "energetics," the structure, and the evolution of our system. The same can be said concerning the majority of other galaxies. This is seen from the fact that the radio-emission power of the cosmic rays is of the same order in both our galaxy and the Andromeda galaxy, amounting to approximately 10^{38} erg/sec; the two irregular galaxies closest to us, the Magellanic clouds, produce one-tenth the radiation, but the dimensions of these galaxies are relatively small. All this goes to show that in "normal" galaxies cosmic rays play approximately the same role as in our own stellar system. But although this role is considerable, the power of the radio emission from the normal galaxies is only a small fraction of their total radiation, concentrated essentially in the visible and infrared parts of the spectrum. Thus, the radiation power of the galaxy is $\sim 10^{44}$ erg/sec, which is 3×10^{10} greater than the radiated power of the sun, namely 3.86×10^{33} erg/sec, and 10^6 times greater than the galactic radio emission power.

There exist, however, anomalous galaxies, also called radio galaxies, the radiation power from which is exceedingly large. One of the most interesting and known radio galaxies is the A Cygni source. Its radio emission power is 6×10^{44} erg/sec, i.e., almost one million times greater than for the galaxy. This, naturally, does not explain the fact that the A Cygni source, which is 600 million light years away from us, is comparable in its brightness on the "radio sky" to the brightness of the sun. It is remarkable that the power of the optical radiation of A Cygni is approximately 10^{44} erg/sec, i.e., several times smaller than its radio-emission power!

What goes into the makeup of this remarkable source? Only recently the prevalent opinion was that A Cygni consists of two colliding galaxies. There were certain grounds for this point of view, since this is a double source (Fig. 13). Now, however, it is believed that more probably we are faced here not with a collision, but rather with a unique "explosion"

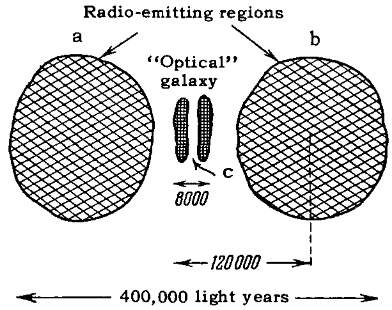


FIG. 13. Schematic diagram of the A Cygni source (not to scale; the dimensions are indicated in light years and are tentative).

of a galaxy. This "explosion" represents, leaving aside the expansion of the entire metagalaxy, i.e., the entire observed system of galaxies, the most grandiose and powerful phenomenon encountered in nature. The cause of the "explosion" of the galaxy in Cygnus has not yet been reliably established, but the approximate course of events is apparently as follows. Several million, or perhaps merely a million years ago, vigorous production of cosmic rays started in some galaxy that had been relatively quiet up to then, or in some tremendous gas cloud, from which the stellar galaxy was later formed. We shall discuss the possible causes of this process at the end of the article. The ever increasing pressure of the cosmic rays caused the fast particles and the magnetic field stuck to them to erupt outward, together with the interstellar gas.

This "eruption" occurred apparently in both directions along the axis of rotation of the galaxy, and has led to the formation of "clouds" a and b, shown in Fig. 13. It is precisely from these "clouds," each greater in dimension than our own galaxy, that the radio emission of A Cygni comes. Between the "clouds" is located the stellar galaxy proper, which is now either a double system, or perhaps contains much dust, and this causes the appearance of a dark middle band (the glowing regions are shown in Fig. 13 cross hatched, and the clear region "c" corresponds to the dark band).

We shall assume that the energy density of the magnetic field and of the cosmic rays are of the same order of magnitude, and that the cosmic rays contain about 1% of electrons (and positrons). We can then estimate the total cosmic-ray energy in the source. In the case of A Cygni such an estimate leads to a value $W \sim 2 \times 10^{60}$ erg (for our galaxy, as we shall see later, $W \sim 10^{56}$ erg). In order to emphasize the enormousness of this figure, let us indicate that the entire rest energy of the sun is $M_{\odot} c^2 = 1.8 \times 10^{54}$ erg, since the mass of the sun is $M_{\odot} = 2 \times 10^{33}$ g. The rest energy of our entire galaxy, which contains approximately 10^{11} stars, is on the order of 3×10^{65} erg.

By emitting radio waves, the electrons lose their energy and consequently the brightness of the source should decrease with time. Thus, were there no "pumping-in" of the cosmic-ray energy in A Cygni, the radio emission would noticeably decrease within a million years.* In other words, sources of the A Cygni type remain exceedingly bright only for a relatively short time. As time goes on, not only should the brightness of the source decrease, but its dimensions should also increase, since the radio-emitting "clouds" of gas and of cosmic rays expand and move away from each other. Consequently there are very few sources such as A Cygni and none other of the same brightness exists at distances comparable with the distance to A Cygni, although millions of galaxies are contained in this region.† There do exist, however, sources which are in some respect analogous, but older and weaker, located even closer than A Cygni.

*According to the assumed values, the energy of the electrons in A Cygni is $0.01\, W \sim 2 \times 10^{58}$ erg, and this source radiates 6×10^{44} erg/sec. It is clear therefore that the energy changes appreciably precisely after 3×10^{13} sec $\simeq 10^6$ years. This time, which is tremendous on human scale, is very short compared with the several billion years which characterize the rate of evolution of most galaxies. The energy "pumping-in" due to formation of new cosmic rays increases the duration of the phase of vigorous radio emission from A Cygni. This increase, however, hardly changes the characteristic lifetime of the source by more than one order of magnitude.

†There is on the average one galaxy in a volume of $(5 \times 10^6$ light years$)^3 \simeq 10^{74}$ cm^3. The farthest galaxy the distance to which could be estimated is 5 – 7 billion light years away from us. It is interesting that even this source (possibly a galaxy of the A Cygni type) was discovered in the radio band.

An example is A Centauri (the galaxy NGC 5128), the structure of which is similar to that shown in Fig. 13, but with dimensions and distances between clouds that are much larger (in addition, the central "optical" regions of the A Cygni and A Centauri sources differ quite strongly from each other). Still older sources may go unnoticed, since the radio-emitting "clouds" become very large and not too bright. The central portion of the radio galaxy can differ little from the normal galaxy. Therefore, essentially, we do not even know whether the majority of normal galaxies go through to some phase of vigorous radio emission. On the other hand, if we group the radio galaxies by their large "present day" brightness,* then there is one radio galaxy for approximately every several thousand normal galaxies.

One must not think that all the radio galaxies, viewed in radio rays, are similar to A Cygni. To the contrary, there exists apparently a great variety of forms, let alone the fact that each galaxy can have its own characteristic features. By way of example of radio galaxies that differ appreciably from A Cygni, we point to A Virginis (the galaxy NGC 4486). This bright radio source is not double and has a very interesting "detail" —a "pip" which is quite bright in visible light (Fig. 14). The radiation from this "pip" has a continuous spectrum, and, what is most important, is strongly polarized. These two features, particularly the presence of polarization, leave no doubt whatever that we deal here with magnetic bremsstrahlung in the optical region of the spectrum. So far we know only of one example of this type—the optical radiation from the Crab nebula (more accurately, that part of the radiation which has a continuous spectrum; the photograph of Fig. 7b was therefore taken practically in the rays of the magnetic bremsstrahlung).

The appearance of optical magnetic bremsstrahlung in the nebulae is connected obviously with the presence in them of a noticeable amount of high-energy electrons.† The optical magnetic bremsstrahlung of the Crab nebula and the "pip" in A Virginis are polarized, since the depolarizing action of the interstellar medium is insignificant at high frequencies, and in addition, small parts of the nebula can be photographed; the

*To avoid misunderstandings we recall that time is reckoned in astronomy from the instant of observation on earth. Therefore when we say that the source A Cygni appears to be bright now, this actually means that it was bright 660 million years ago, the time required for the light to reach us from that source.

†As can be readily verified with the aid of formula (7), for example, in a field $H_{\perp} \sim 3 \times 10^{-4}$ oe for electrons with energy $E \sim 5 \times 10^{11}$ ev, the maximum in the spectrum of magnetic bremstrahlung corresponds to a wavelength $\lambda_{max} = c/\nu_{max} \sim 7{,}000$ A, i.e., it lies in the visible portion of the spectrum. Under laboratory conditions (in synchrotrons) in a field $H \sim 5{,}000$ oe, a similar radiation spectrum is produced by electrons of energy $E \sim 100$ Mev $= 10^8$ ev. The magnetic optical bremsstrahlung in synchrotrons is observed without particular difficulty.

FIG. 14. Photograph of the brightest (central) part of the radio galaxy NGC 4486 (radio source A Virginis). The bright "pip" appears to consist of separate "beads."

degree of polarization of the optical radiation of the entire Crab nebula amounts to 9%, and in individual small regions of the nebula the polarization is almost complete. Furthermore, on centimeter radio waves the polarization of the Crab nebula is also still noticeable (on 10 cm wavelength it is approximately 30%, but on 20 cm it is less than 1%).

The Crab nebula (it is also called A Tauri) is located in the galaxy some 4500 light years away from us. This nebula was formed in 1054 A.D. as a result of a supernova explosion. Through a fortunate coincidence, this star was located not only relatively closely, but in a region with relatively "clean sky," i.e., containing an insignificant amount of cosmic dust. The brightness of the burst of the 1054 supernova was so high that it was readily observed during the daytime, whereas Venus, the brightest of all stars and planets, can rarely be seen during the day. Naturally, such an event did not pass unnoticed and the appearance of a new star* in the Taurus constellation was recorded in Japanese and Chinese annals. It is precisely in this place that we now see the Crab nebula.

The explosion of a supernova is the most powerful phenomenon encountered in galaxies. Several weeks after the explosion the brightness of the optical radiation of the supernova is comparable with the brightness of the entire galaxy in which this star has burst. This means that the irradiated power of the supernova at the maximum of brightness can exceed by many billions of times the radiated power from the sun.

The frequency of supernova bursts in the galaxy has not been accurately established. Apparently, supernovae burst on the average once every 30 — 100 years. The difficulty in determining the frequency of the burst is due to interstellar absorption of the light, which makes observation of supernova in the galaxy difficult, and also the relative scarcity of bursts. Bursts of supernovae in other galaxies are easier to notice. The frequency of the bursts depends on the type of galaxy; typical for spiral galaxies is apparently the appearance of supernovae once every many decades or once every several centuries.

The nature of the supernova bursts has not yet been established. One of the possible hypotheses is that in

*In a narrower sense or, if convenient, in a specialized sense, the term "new star" or simply "nova" is applied to bursting stars, the brightness of which is thousands of times smaller than the brightness of the star in Taurus during its burst. This is why this star and analogous objects are referred to, with little justification, as "supernova star" or more frequently "supernova." About some 100–200 novae are produced in the galaxy every year, but only one or two can be noticed, owing to the interstellar absorption of light. The frequency of supernova bursts will be discussed somewhat later.

some particularly large young stars there occurs, during the course of evolution, a rapid contraction of the central region, possible with formation of a neutron nucleus. (Stellar evolution, as it is well known, is connected with the course of thermonuclear reactions inside the star. Abrupt changes in the course of these reactions are due to the "burn up" of some of the elements.) The gravitational energy released upon contraction causes the entire external part of the star to explode and scatter. Probably, the expanding shells of supernovae are produced in this fashion. In the Crab nebula the shell moves with a velocity of approximately 1,000 km/sec. For comparison we recall that the velocity of the closely-lying earth satellites is 8 km/sec. Over the 907 years from the instant of the explosion, the fragments of the shell have covered a distance of approximately three light years, to which the present radius of the Crab nebula amounts. It is remarkable that the "young" shells of the supernovae are powerful sources of nonthermal cosmic radio emission. We have already mentioned the Crab nebula. Radio waves, although somewhat weaker, are emitted also by other "historic" supernovae: the Tycho Brahe supernova (1572 A.D.), the Keppler supernova (1604), and a few others. Finally, it has been established that the most powerful source of nonthermal radio emission on the sky, A Cassiopeiae, is the shell of a supernova that burst some 250 years ago. The optical effect of the burst of this supernova was not noticed owing to the insterstellar absorption of light (the distance to A Cassiopeiae is on the order of 10,000 light years). The rate of scattering of the shell of this supernova exceeds 7,000 km/sec!

There is no shadow of a doubt that the powerful radio emission from the supernova shells is connected with the presence in these shells of a large amount of relativistic electrons. There is much evidence that the shells contain also a large number of other high-energy particles, i.e., many cosmic rays.

Let us summarize. Cosmic rays are found in all galaxies, they are exceedingly plentiful in radio galaxies, and they are formed in large amounts in supernova shells, and they emit radio waves. Thus, radio astronomy has tremendously added to our knowledge of cosmic rays and has ascertained that they are found everywhere in the universe.

3. ORIGIN OF COSMIC RAYS

The observed data offer evidence that cosmic rays are known to be formed on the sun and also during explosions of supernovae. (Unless otherwise stipulated, we shall speak henceforth only of our own galaxy.) It is natural to think that other stars can also emit cosmic rays. But what is the role of the various sources and how were the cosmic rays reaching the earth produced? How are the charged particles accelerated to the cosmic-ray energy as a result of supernova bursts, and also on the sun or other stars?

These questions should be answered by the theory of the origin of cosmic rays.

a) Energy Balance. Sources of Cosmic Rays

One of the most important requirements that the sources of cosmic rays must satisfy is based on energy considerations.

The protons and nuclei, which make up the bulk of the cosmic rays, lose energy all the time by collision with the nuclei of the interstellar medium. The effective cross sections σ for such collisions are known, although not very accurately—they are listed in Table II for collisions between different groups of nuclei moving in hydrogen. The composition of the interstellar gas mixture is given in Table I. The differences that result from taking this fact into account, however, are small and of no significance in principle, owing to the inaccurate knowledge of the density of the interstellar medium. Table II indicates also the mean free paths l in g/cm^2 and the mean free path times for a medium with average hydrogen concentration $\bar{n} = 0.01\ \text{cm}^{-3}$.*

Table II. Effective cross sections, ranges, and lifetimes of cosmic rays

Group of nuclei	Effective cross section σ_i in units of 10^{-26} cm^2	Mean free path l, in g/cm^2	Lifetime T_{nuc} in years
P	2.26	74	$5\cdot10^9$
α	10	16.5	10^9
L	19.3	8.7	$5\cdot10^8$
M	28	6.0	$4\cdot10^8$
H	48	3.5	$2.5\cdot10^8$
VH (Fe)	71	2.4	$1.5\cdot10^8$

The heavy nuclei disintegrate into lighter nuclei and protons, but the average energy per nucleon changes relatively slowly. The energy losses of the cosmic rays are determined consequently by the nuclear lifetime of the protons, $T_p \sim 5 \times 10^9$ years $\cong 1.5 \times 10^{17}$ sec (we recall that one year = 3.16×10^7 sec). This situation, however, prevails only in the absence of losses other than those due to nuclear collisions. In practice, for protons and nuclei with cosmic-ray energy, it is necessary to account only for the escape of cosmic rays from the galaxy (from the halo) into metagalactic space in addition to accounting for nu-

*The mean free path l, by definition, is equal to $1/\sigma\bar{n}$, where σ is the effective cross section and $\bar{n}$ is the average concentration of the nuclei of the medium, (in this case the nuclei of hydrogen or protons); the quantities l, σ_i and $\bar{n}$ are respectively measured, for example, in cm, cm^2, and cm^{-3}. The length l in g/cm^2 is equal to $\bar{\rho}/\sigma\bar{n}$, where $\bar{\rho} = \overline{Mn}$ is the average density of the medium and M is the mass of the nuclei making up the medium. For hydrogen, $M = M_p = 1.67 \times 10^{-24}$ g. The free path time T_{nuc} for collisions with mean free path $l = 1/\sigma\bar{n}$ is $T_{nuc} = l/v \simeq l/c = 1/\sigma\bar{n}c$, for in practice the velocity v of cosmic rays is equal to the velocity of light c.

clear collisions. Unfortunately, the time T_e characterizing such an escape of particles, is not known accurately. One might think that the time T_e is either greater than T_{nuc} or at least one-tenth as large. Therefore, taking into account the tentative nature of the following estimates, we can assume that from the point of view of energy loss the effective lifetime of the cosmic rays in the galaxy is on the order of $T_p \sim 10^{17}$ sec. This time is less than the age of the galaxy, $T_G \sim 10^{10}$ years $\cong 3 \times 10^{17}$ sec. What is particularly important is that for the VH nuclei $T_{VH} \simeq T_{Fe} \sim 1.5 \times 10^8$ years $\cong 3 \times 10^{15}$ sec $\ll T_G$. By virtue of the latter inequality, it is clear that the cosmic rays now observed, which originated mostly as VH nuclei, are "young" in terms of the age of the galaxy.

The volume of the galactic halo filled with cosmic rays is approximately $V \sim 4\pi R^3/3 \sim 10^{68}$ cm^3, since the average radius of the halo is $R \sim 3 \times 10^4$ light years $\cong 3 \times 10^{22}$ sec. Taking for the average energy density of the cosmic rays in the halo a value $\bar{w} \sim 0.3$ ev/cm$^3 \simeq 5 \times 10^{-13}$ erg/cm^3, we obtain directly the total energy of the cosmic rays in the galaxy, $W = wV \sim 10^{56}$ erg. Were the influx of new cosmic rays to cease, the total energy of the cosmic rays in the system would change appreciably after a lifetime $T_p \sim 10^{17}$ sec. This obviously means that to maintain an equilibrium wherein the cosmic-ray energy in the galaxy remains unchanged* the sources of these rays should have a power

$$U \sim \frac{W}{T_p} \sim 10^{39} - 10^{40} \text{erg/sec} \tag{10}$$

and the greater of these values has been cited to provide a certain "margin" for inaccuracy in the calculations.

A source power $10^{39} - 10^{40}$ erg/sec is not so easy to come by; for example, the sun emits cosmic rays with an average power which apparently does not exceed $10^{22} - 10^{23}$ erg/sec. Therefore even if the 10^{11} stars of the galaxy were all to have the same cosmic-ray power as the sun, they would produce $10^6 - 10^8$ times less cosmic rays than required to maintain the balance. This example is quite instructive. The mere statement that the cosmic rays can be generated on the stars does not yet explain the origin of the observed cosmic rays. To verify the "stellar" origin of cosmic rays, it is necessary, in addition, to assume that many stars emit cosmic rays much more efficiently than the sun. This subjects to grave doubts the hypothesis that the bulk of cosmic rays are of stellar origin. In addition to energy considerations, we also point out the fact that the solar cosmic rays have an entirely different spectrum and chemical composition than the cosmic rays arriving from interstellar space. (To avoid misunderstanding, we note that when we refer to the stellar origin of cosmic rays we have in mind only the acceleration of particles by non-exploding stars.) In our opinion, there are no serious grounds whatever at present to support the hypothesis of stellar origin of cosmic rays, all the more since the cosmic rays can be attributed to supernova bursts.

*During the last several billion years, the galaxy changed but little. There is therefore every reason for assuming that the picture is stationary, since the VH nuclei now observed on earth were formed only several hundred million years ago.

We can cite several arguments in favor of this explanation. The presence in the supernova shells of a large number of electrons with cosmic-ray energies has been firmly established. The energy of these electrons in the Crab nebula and in A Cassiopeiae amounts to $10^{47} - 10^{48}$ ergs. The energy of all the cosmic rays in these sources is some hundred times greater.* Consequently, each supernova burst is accompanied by a cosmic-ray energy up to $10^{49} - 10^{50}$ ergs or even more, if it is recognized that some of the cosmic rays can leave the shell even before the latter diffuses. Within 50 — 150 thousand years after the explosion of the star, the shell is practically all scattered in the interstellar medium and the cosmic rays fall in the "common pot." This occurs principally in regions where the number of stars is the greatest—in the galactic spiral and in the central regions of the galaxy. But the cosmic rays do not stay long in their place of birth, for they move along the force lines of the field and fill the entire halo.

The average power of the cosmic rays injected in this manner is obviously equal to the energy per burst, $W_b \sim 10^{49} - 10^{50}$ erg, divided by the average time between bursts, T_b, equal to 30 — 100 years. Consequently the power of the cosmic rays produced by the supernovae is

$$U_{sn} \sim \frac{W_b}{T_b} \sim 10^{39} - 3 \cdot 10^{40} \text{ erg/sec.} \tag{11}$$

Comparing this value with the necessary power (10), we readily see that the supernovae can provide the energy balance. We must point out, in addition, that there are no observations whatever to indicate that there exist in the galaxy other sources of cosmic rays, whose power is comparable with the power of such sources as supernovae. If we speak not of observations but of more or less reasonable estimates, an important role can possibly be ascribed to novae. The energy released during their explosion is thousands of times less than that of supernovae, but the frequency of explosions of the former is thousands of times greater. The fact that no radio emission from novae has yet been observed is still not decisive, since very weak sources are difficult to spot and to identify.

These are the basic reasons for assuming that it

*This value is obtained from a comparison with data on cosmic rays in the galaxy, from considerations of approximate equality of the energy of the cosmic rays and the energy of the magnetic field, and also from the analysis of the dynamics of scattering of the shells.

is precisely the supernovae which are the main "suppliers" of cosmic rays in the galaxy. The same can probably be said of all normal galaxies. It is not excluded that some features of radio galaxies are also influenced by supernovae and can be attributed to the sharp increase in the frequency of supernova bursts during a certain state of galactic evolution. Another explanation possible in principle is that the cosmic rays are effectively accelerated by the process of vigorous star formation. These, however, are merely assumptions, and the nature of radio galaxies still remains undecided.

Thus, from the point of view developed, the cosmic rays that reach the earth originate in bursts of supernovae.* Here, naturally, only some of the cosmic rays arrive to us directly from the supernova shells; the other part is the product of nuclear collisions in the interstellar medium. This fact was already discussed in connection with light nuclei and protons. We merely emphasize here that secondary processes contribute much to the formation of the electrons and positrons. Nuclear collisions between high-energy particles give rise to charged or neutral pions. The latter decay with emission of gamma rays, which leave the galaxy almost without obstacles. As regards the charged pions, their decay leads in final analysis to the formation of electrons and positrons ($\pi^{\pm} \rightarrow \mu^{\pm} + \nu$, $\mu^{\pm} \rightarrow e^{\pm} + \nu + \bar{\nu}$).

About 5% of the energy of the primary nucleons goes into the electron-positron component; the primary nucleons lose in our entire galaxy a total of $10^{39} - 10^{40}$ erg/sec by nuclear collision. It follows therefore that the fraction going into electrons and positrons is

$$U_e \sim 5 \cdot 10^{-2} U \sim 5 \cdot 10^{37} - 5 \cdot 10^{38} \text{ erg/sec.} \qquad (12)$$

The power of the entire galactic radio emission is on the order of 10^{38} erg/sec, so that the secondary electrons and positrons alone could balance the energy of the electron-positron component of the cosmic rays. On the other hand, some electrons should go into interstellar space from the supernova shells, where these electrons are known to exist. At the present time it appears more likely that the principal role is played in our galaxy by electrons and positrons of secondary origin, i.e., the products of the $\pi \rightarrow \mu \rightarrow e$ decay in the interstellar medium.

b) Mechanism of Acceleration

A very important feature of the suggested origin of cosmic rays is that it is based on radio-astronomy data, which offer evidence of the presence of cosmic rays in shells of supernovae. This is precisely why we can in some respect separate the question of the sources of cosmic rays from the question of the mechanism of their acceleration in these sources. In other words, all our conclusions, fortunately, are independent of the exact manner in which the particles are accelerated in space to relativistic energies. At the same time, naturally, the last-mentioned problem is also worthy of every attention.

The question of the mechanisms whereby particles are accelerated on the sun, in supernovae shells, and other regions of the universe is far from completely answered. Nonetheless, many ideas can already be advanced. With one single exception—acceleration in a shock wave with rising amplitude—all the known real mechanisms of acceleration of charged particles in space are connected in one manner or another with the action of the electric field induced by a rise in the magnetic field. The simplest electromagnetic mechanism is betatron acceleration, and in this case the acceleration is due to the rise in the homogeneous (or quasi-homogeneous) magnetic field with time. If we leave out stars, then a considerable and prolonged rise in a magnetic field is usually not encountered under cosmic conditions.* In this connection, great interest is attached to the acceleration connected with the "collisions" between the particle and the moving inhomogeneities of the magnetic field. In such a collision (Fig. 15) the particles are accelerated in final analysis by the electric field induced by moving gas masses with "frozen-in" magnetic field.† We can, however, disregard the collision process itself, and consider only its result. For this purpose it is sufficient to use the energy and momentum conservation laws. (Strictly speaking, we examine in this manner all other collisions, for example, the collision between a steel ball and a metal or stone plate; in this case the ball penetrates somewhat into the plate during the time of the collision itself, the same as in Fig. 15a.) It can also be stated that a real collision (Fig. 15a) is replaced by an equivalent collision (from the point of view of the final result) of the reflected particle with an impenetrable wall, moving at the same velocity **u** (Fig. 15b).

From the conservation laws it follows that upon collision the change ΔE in the total particle energy E is

*An exception are the solar cosmic rays (the remaining non-exploding stars probably make a negligible contribution to the total flux of cosmic radiation). Other possible exceptions are the particles with the highest encountered energies ($E \sim 10^{18} - 10^{19}$ ev). If these particles are protons, they should be of metagalactic origin (see Sec. 1b). This important problem will remain unsolved until the chemical composition of ultra-high-energy cosmic rays is determined.

*The betatron mechanism can be quite significant on the sun and in stars during the appearance of spots, and also in so-called magnetic stars. Here we are interested primarily in other conditions (supernova shells etc.).

†In the case of motion of a highly conducting medium, such as ionized interstellar gas, in a reference frame connected with the medium, the electric field is practically zero. If a magnetic field of intensity **H** is also present and the medium moves with velocity **u** relative to the frame of interest to us, we have in this system an electric field with intensity $E = \mathbf{u} \times \mathbf{H}/c$ (we assume that $u \ll c$).

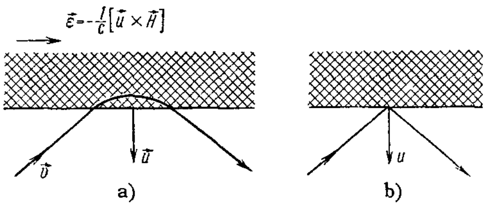


FIG. 15. "Collision" between cosmic particle and moving inhomogeneity of magnetic field. The magnetic field in the shaded region (gas cloud) moves with velocity **u** in a direction perpendicular to the plane of the diagram (there is no field outside this region). a) Real collision; b) "equivalent" collision.

$$\Delta E = -\frac{2E}{c^2}(\mathbf{uv}), \tag{13}$$

where **v** is the velocity of the particle prior to collision and $u \ll v$ (in the calculation we use also the fact that the particle energy is negligibly small compared with the kinetic energy of the wall). From formula (12) it is clear, for example, that for any impact between the particle and a wall moving head-on towards it, the energy of the particle increases by $\Delta E = (2E/c^2)uv$ (the total energy of a relativistic particle is $E \cong Mc^2$ and $\Delta E \cong 2Muv$).

We assume now that there are two "walls" moving towards each other. The role of these walls can be played, under cosmic conditions, by the fronts of magnetohydrodynamic shock waves or gas masses carrying magnetic fields. The charged particle falling into the space between the walls (Fig. 16) will then be accelerated until it leaves the system or until the distance between the walls becomes comparable with the radius of curvature of the particle trajectory in the magnetic field of the walls. The total increment of particle energy is obviously equal to the change in energy during one collision, multiplied by the number of collisions. This is the mechanism whereby particles are systematically accelerated in a moving medium with magnetic fields. This mechanism is relatively quite effective (the acceleration is proportional to u/c and, for example, when u = 3,000 km/sec, the energy of the relativistic particle doubles as a result of n = c/2 = 50 collisions. The systematic acceleration, however, cannot continue long for the walls come together after a certain time. Therefore, generally speaking, a more important role is played under cosmic conditions by the so-called *statistical acceleration*. In statistical acceleration the particle experiences both head-on collisions and "tail-on" collisions, when the particle energy decreases. However, the head-on collisions are somewhat more probable and on the average the particle energy increases, but this increase is no longer proportional to u/c, but to u^2/c^2. Naturally, the rate of energy buildup is less in this case (we recall that $u/c \ll 1$), but on the other hand the acceleration process can continue for a very long time (the acceleration period is determined by the time required for the particle to leave the region of the moving gas masses, by the time of the existence of vigorous motion in the shell of the star, etc.).

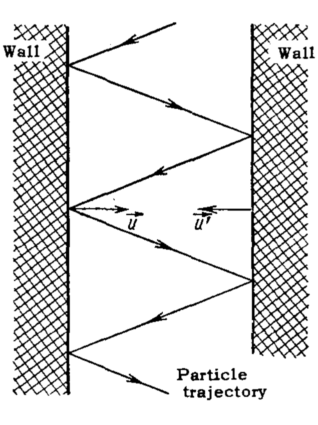


FIG. 16. Acceleration between walls moving towards each other (wall velocities **u** and **u'**).

In the case of a supernova explosion and subsequent expansion of the shell, the details of the acceleration process still remain unclear. This is understandable, if it is recognized that we know very little about the course of the explosion itself and the shell formation. One can state with assurance only that the shells contain all the "ingredients" necessary to accelerate the moving gas masses, namely magnetic fields and sufficiently fast particles.

This last condition is connected with the existence of injection energy. The point is that the particle may fail to acquire energy even in the presence of accelerating mechanisms, owing to the predominance of the retarding mechanisms. These include primarily the ionization losses—when a charged particle moves in a medium, it loses energy to ionization of this medium. In a fully ionized medium, these losses also exist, and the particle energy is consumed in this case, roughly speaking, in "pushing apart" the particles of the medium. The term "ionization losses" must therefore not be taken literally.

The ionization loss rate (the magnitude of the losses per unit time, S_{ion}) depends on the kinetic energy of the particle E_k, as shown in Fig. 17. The losses reach a maximum at a particle velocity v equal to approximately the velocity v_e of the electrons

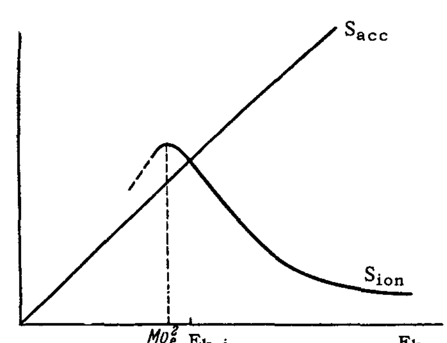


FIG. 17. Rate of ionization loss (S_{ion}) and rate of energy rise due to acceleration, (S_{acc}) as functions of the kinetic energy E_k of the particle.

of the medium, in which the particle moves (the kinetic energy of the particle at the loss maximum $E_{k,max}$ is therefore approximately equal to $Mv_e^2/2$). The rate of energy buildup as a result of the action of the accelerating mechanisms (S_{acc}) usually increases monotonically with increasing E_k. In the simplest case this rate is simply proportional to E_k, as is assumed in Fig. 17. The curves $S_{ion}(E_k)_k$ and $S_{acc}^k(E_k)_k$ intersect in Fig. 17 at a point corresponding to a certain energy $E_{k,i}$. This value is called the injection energy —the acceleration occurs only when the particle has somehow acquired beforehand an energy E_k greater than $E_{k,i}$. But there is one important exception to this rule: the particle can be accelerated without injection (prior acceleration), if the curve S_{acc} passes over the maximum of the S_{ion} curve (see curves 1 and 3 in Fig. 18). For a particle (ion) with a given charge, the loss curves $S_{ion}(E_k)$ shift to the right with increasing particle mass M. This is quite understandable: the losses are maximal when $v \simeq v_e$, i.e., when $E_{k,max} \simeq Mv_e^2/2$.

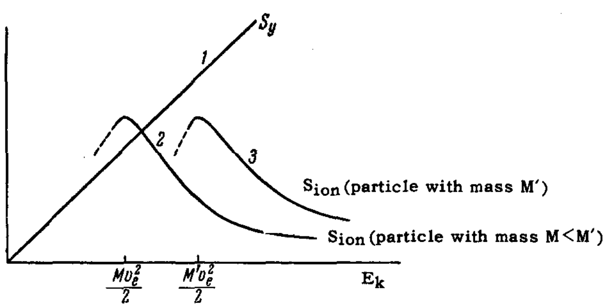


FIG. 18. A sufficiently heavy particle can be accelerated without injection (curves 1 and 3). For lighter particle, injection (preliminary acceleration) becomes essential (curves 1 and 2).

This leads to a conclusion, which can be of basic significance from the point of view of the problem of acceleration of cosmic rays. Conditions are possible, and these correspond precisely to Fig. 18, when injection is necessary for the lighter particles, but not for the heavier ones. Under these conditions, there will be a preferred acceleration of the heavy particles, and consequently, the cosmic rays should consist essentially of heavy nuclei. Moreover, there are grounds for assuming that conditions favoring the acceleration of heavy particles only are not the exception but the rule. It is precisely in this way that one can hope to understand the fact that there are particularly many heavy nuclei in the cosmic rays.

CONCLUSION

What can be expected from a further study of cosmic rays on earth and in space?

An attempt to answer the question, although frequently made, would hardly be sensible: the most interesting, probably, will turn out to be the most unexpected results of the future researches. On the other hand, one can indicate without vacillation certain questions, the answers to which would be particularly important.

The most important in the study of primary cosmic rays on earth would be the following:

1. To measure the flux of electrons, positrons, and gamma rays. If the flux of the primary cosmic rays on earth contains approximately equal amounts of both electrons and positrons, there is no doubt of the secondary origin of these particles, i.e., they are formed by $\pi^\pm \to \mu^\pm \to e^\pm$ decay, and not by acceleration in an ionized gas that contains no positrons.

2. To determine much more accurately the chemical composition of the cosmic rays at not too high energies.

3. To ascertain, albeit crudely, the chemical composition of cosmic rays with very high energies ($E > 10^{16}$ ev).

4. To determine with high accuracy the energy spectrum of the cosmic rays with energy $E > 10^{14} - 10^{15}$ ev. To measure the coefficient of anisotropy δ for cosmic rays of different energy.

Radio-astronomic and astrophysical methods make it possible presumably to obtain new or more complete exact information on the cosmic rays in the supernova shells, in the galactic spiral and halo, in other galaxies, and in intergalactic space. The last factor is perhaps particularly important for an explanation of the role of cosmic rays in the entire metagalaxy. The problem of the origin and evolution of cosmic rays is now intertwined with cosmology. The same, moreover, can be said of the nature of the radio galaxies.

Among the sources of information on cosmic rays we can also include a theoretical analysis of the mechanisms of particle acceleration, the explosion of supernovae and the scattering of the shells, and the evolution of the galaxies and the metagalaxy.

The vigorous development of the experimental techniques (including the use of satellites, rockets, and giant radio telescopes), and also the progress in theoretical astrophysics, leave no doubt that many of these problems will be essentially solved even in the nearest future.

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This article is designed for a wide circle of readers, and consequently no references are given to the specialized literature. The history of development of cosmic-ray physics, particularly in the U.S.S.R., has been detailed by Dobrotin.[1] The main problems discussed in this article are considered in detail in references 2 and 3.

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