PRESENT STATUS OF THE QUESTION OF THE ORIGIN OF COSMIC RAYS

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INTRODUCTION

THE question of the origin of cosmic rays continues to attract much attention. This is quite understandable, for the problem of the origin of cosmic rays is closely connected with radio astronomy, the physics of the stars (particularly supernovae), the physics of the sun, the properties of interplanetary and interstellar media, and the theory of particle acceleration.

An idea of the most recent data concerning primary cosmic rays could be gained at the International Conference on Cosmic Rays, held in Moscow in July 1959. The preparations and proceedings of the conference were devoted to an analysis and discussion of many important problems. The present article is an attempt to summarize the progress made to date, with inclusion of results obtained after the conference. We shall start out with ideas based on radio-astronomical data, developed in detail in reference 1. According to these ideas* cosmic rays are essentially of galactic origin and are formed primarily as supernova flares and perhaps of other non-stationary stars. The main problem here, however, is not so much the identification of the sources (although it is very important) as the gathering of information on the spectrum, intensity, and spatial distribution of cosmic radio waves in the galaxy and beyond its limit, so as to determine the energy spectrum, amount, and spatial distribution of the electrons (and positrons) which form the electronic component of the cosmic rays. It is precisely the use of radio-astronomic data in conjunction with information on primary cosmic rays near the earth that have given rise to the question of the origin of cosmic rays, along with other astrophysical problems, which are being solved with the aid of observations.

We shall present basic new information concerning primary cosmic rays near the earth (Sec. 1) and cosmic radio waves (Sec. 2). Then, in Secs. 3 and 4, we shall discuss the lifetime and the character of motion of the cosmic rays in the galaxy and in the metagalaxy, the sources of cosmic rays and their mechanism of acceleration, the transformation of the nuclear component of cosmic rays in the interstellar medium, etc.

*In addition to reference 1, the general status of the problem of the origin of cosmic rays (latest reviews) is discussed in references 2 and 3 (see also the Proceedings of the Varenna Conference on the Physics of Cosmic Rays[4]).

TABLE I

Group	Z	$\bar{A}$	Flux I $\frac{\text{particles}}{\text{m}^2\text{ sr-sec}}$	Number of nucleons in the flux	$\frac{I}{I_H}=\frac{N}{N_H}$	In the universe (average)	
						$\left(\frac{N}{N_H}\right)$ ref. 23	$\left(\frac{N}{N_H}\right)$ ref. 24
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
Total number of nucleons				1827			

1. PRIMARY COSMIC RAYS NEAR THE EARTH

The principal experimentally-observed characteristics of primary cosmic radiation are the chemical composition, the energy spectrum, the minimum energy (high-latitude cutoff), the maximum energy, and the isotropy. Reliable measurements of these quantities are a necessary basis for a determination of the origin of cosmic rays. Study of cosmic rays has led recently to considerable progress in knowledge of the properties of the primary radiation, and gives grounds for hoping that many debated points will be resolved in the nearest years.

a) Chemical Composition

To increase the statistical reliability of the experimental data, it is customary to gather nuclei with nearly equal atomic numbers Z into groups (see Table I). The percentages of the various elements within each group are still not known with sufficient reliability,[5,6] but these data do permit an estimate of the average atomic weight $\bar{A}$ of a given group (see column 3 of Table I). The 4th column of Table I gives the absolute fluxes I of nuclei with total energy $\epsilon > 2.5$ Bev/nucleon,* extrapolated to the top of the atmosphere, corresponding to geomagnetic latitudes of approximately 41° for nuclei with $Z \geq 2$ and approximately 51° for protons. Without stopping to analyze the data on these fluxes (see reference 5), we offer merely a few explanations of Table I.

In the indicated energy regions, the fluxes are still sufficiently sensitive to the level of solar activity,[7] diminishing noticeably (to 30%) during the maximum period (1957 — 1958), compared with the minimum period (1954 — 1955). The data given on the p and α fluxes pertain to the minimum of solar activity, while for the remaining groups of nuclei such a differentiation is meaningless, since the accuracy of flux measurement is low. We can assume, although this has not yet been proved (see references 5 and 8), that during years of minimum solar activity the cosmic rays that enter the solar system from the outside are least perturbed, and measurements yield then values which are close to the true fluxes of cosmic rays in the adjacent region of the galaxy.

Protons make up the bulk of cosmic radiation, and this accounts for the relatively high statistical accuracy of the measurements. However, the difficulty of accounting for the albedo, and the fact that the cosmic-ray flux is not constant even in years of low solar activity, lead to a large spread in the results of different workers. Table I lists the value obtained in reference 9, for a latitude of 51°, in 1952 and 1954.

The most reliable are the measurements of the flux of alpha particles; according to workers,[10-12] this amounts to approximately 90 ± 9 particles/m^{2}sr-sec, which agrees also with the most probable value assumed in reference 5.

In the case of the heavier nuclei, one measures in the experiments the flux or the relative fraction of different nuclei (groups of nuclei) at different depths of the atmosphere, principally at the pilot-balloon altitudes. The results of recent measurements are as a whole in satisfactory agreement. However, further extrapolation to the top of the atmosphere, necessary for the determination of the composition of the primary radiation undistorted by the splitting of heavy nuclei, is a major source of errors. In addition, such an extrapolation, even if the composition of the cosmic rays at a given depth of the atmosphere is known in detail, unavoidably masks the finer properties of the composition (relative composition of different groups of nuclei, the presence of elements of low natural abundance, isotopic composition, etc.). It is therefore extremely important for the theory of cosmic rays to measure directly the composition above the top of the atmosphere.

Among the nuclei with $Z > 2$, the flux of group M, i.e., of C, N, O, and F, has been determined with relative reliability. According to different data, it

*The quantity I is more correctly defined as an intensity, since the flux is $F = \int I d\Omega$, where $d\Omega$ is the element of solid angle (see reference 1). The terminology used in the text is more conventional, and, with this qualifying statement, should lead to no misunderstanding.

lies in the range $I_M = 5.1$ to 6.1 particles/m^2 sr-sec. The average value $I_M = 5.6$ listed in the table agrees with the data of references 10 and 13 — 15, and also with the average in reference 5.

The measured ratio I_H/I_M fluctuates essentially from 0.4 (see references 10, 16, and 17) to 0.5 (see references 13 — 15). Following reference 5, we choose as the most probable ratio $I_H/I_M = 0.45$, corresponding to $I_H = 2.5$ in the table.

The very acute problem concerning the presence of L nuclei (Li, Be, B) in the primary component, has been recently clarified somewhat. In most papers (see references 10, 14, 15, and 17) a value $I_L/I_H \approx 1/3$ is given, as assumed in Table I (larger values of I_L/I_M are also encountered; see references 7, 13, and 16). The results of reference 18, which gives $I_L/I_M < 0.1$, are in sharp disagreement. This disagreement is connected to a considerable extent with the method used to extrapolate to the top of the atmosphere, and was critically analyzed in references 5, 7, and 19. In this connection, particular notice must be taken of reference 20, in which the data have been obtained for a record altitude (the thickness of the residual atmosphere is 2.7 g/cm^2), and where the need for extrapolation is eliminated to a considerable extent. In this reference, a preliminary reduction of the data yielded a ratio $I_L/(I_M + I_H) = 0.18 \pm 0.06$ for vertically arriving particles. It follows hence that $I_L/I_M = 0.26$ when $I_H/I_M = 0.45$. Thus, there is apparently no doubt now of the existence of a noticeable primary flux of the nuclei Li, Be, and B. We can hope that this question can be finally resolved in the nearest future quantitatively, too.

It became possible recently to segregate in the H group a subgroup VH of "very heavy" nuclei ($Z \geq 20$). The main part of this subgroup is apparently made up of Fe and Cr.[5,21] The flux ratio I_{VH}/I_H is, according to reference 5, 0.26 to 0.28. For higher energies (at the equator) $I_{VH}/I_H = 0.30 \pm 0.07$.[22] We note that reference 5 cites directly values of 0.35 ± 0.10 and 0.38 ± 0.08 for $I_{VH}/(I_H - I_{VH})$, depending on the source of the data. According to reference 21, $I_{VH}/(I_H - I_{VH}) = 0.48 \pm 0.14$. In Table I we use $I_{VH}/I_H = 0.28$.

It is still too early to judge with any certainty the finer details of the composition, but certain conclusions can nevertheless be drawn. Thus, nuclei with even Z are more abundant in the cosmic rays, and in the universe as a whole, than those with odd Z (incidentally, this feature is apparently less sharply pronounced in cosmic rays). It is interesting to note that there is more B than Li and more C than O in cosmic rays, whereas in the universe, on the average, the opposite is true. We notice also that fluorine, which has an extremely low abundance in nature, is apparently present in cosmic rays in noticeable quantities.[5]

There are certain indications (see references 5 and 21) that "gaps" exist in the charge spectrum of the cosmic rays (for example, there are few nuclei with Z = 17 — 23, and as already noted, few nuclei with odd Z). If deep "gaps" actually exist, this may be a very important factor. In fact, if only heavy nuclei are accelerated (see Sec. 4), then the stable nuclei that result from the disintegrations should seemingly have a more or less uniform distribution with respect to Z and A (this remark was made by B. Peters). Such a statement, naturally, is not beyond doubt, but it can be verified under laboratory conditions, by investigating the products of disintegration of heavy nuclei, induced by a beam of protons or α particles. Thus, if the "gaps" cannot be the result of singularities in the disintegrations, then their presence in cosmic rays would be evidence against the hypothesis that only heavy nuclei are primarily accelerated.

The 5th column of Table I indicates the number of nucleons contained in each of the charge components of cosmic rays. Almost 1/3 (more accurately, 29%) of nucleons with a given energy are attributed to the nuclei with $Z \geq 2$. It is interesting to note that at a given geomagnetic latitude (i.e., at a specified magnetic hardness) the nucleons contained in the nuclei with $Z \geq 2$ carry almost half the cosmic-ray energy.

Column 6 of the table contains the ratio of the nuclear flux of a given group to the flux of heavy nuclei, which obviously is equal to the ratio of the concentration N of these nuclei in cosmic rays (we refer to particles with $\epsilon \gtrsim 2.5$ Bev/nucleon, the velocities of which are quite close to the velocity of light c).

Finally, columns 7 and 8 give the abundance of the elements of the corresponding groups in the universe, referred to the abundance of the nuclei of the H group, according to the data of references 23 and 24. The following important feature is striking: the cosmic rays are much poorer in light elements than the region of the universe known to us. New data on the abundance of elements in the universe[24] make this difference even stronger. It becomes particularly sharp if we compare the number of nuclei per very heavy VH nucleus in cosmic rays and in the universe. Then the ratio of the number of protons and α particles to the number of heavy nuclei is two orders of magnitude smaller in the cosmic rays than in the universe on the average. The consequences of this will be discussed in Sec. 4d.

There is apparently no further increase in the excess of heavy nuclei in the region of still larger Z. Measurements of $I(Z > 35)/I(Z > 17)$, carried out with an artificial satellite,[25] have shown that this ratio does not exceed the value expected for natural abundance. These data are, however, still tentative.

b) Energy Spectrum

Over a wide range of energies, the particle flux has the following power-law dependence on the energy

TABLE II

Group of nuclei	$\gamma_A - 1$	K_A	Energy interval, Bev/nucleon	Reference
p	1,5	6600	4.0—16.0	11,30
	1.40±0.10	4800	4.7—16.0	31
	1.40±0.22	—	65—300	32
	1.45±0.25		16—5000	33
α	1.49±0.22	360	2.5—800	34
	1.45±0.11	300	2.5—8.0	31
	1.5	415	1.3—8.0	11,30
	1.58±0.20	—	8—1500	22
	1.48±0.12	360	1.4—4.0	34
$M+H$	1.54±0.16	—	2.6—50	14
	1.6 ±0.15	—	8—100	22
	1.51±0.18	—	2.5—8.0	31
	1.70±0.25	—	1.23—10.0	35
M	1.35±0.15	—	1.4—50	36
	1.65±0.30	—	1.23—10	35
	1.57±0.20	—	8—100	22
	1.57±0.12	25.4±4.2	2.5—8	16
	1.51±0.1	—	2.5—8	5
	1.6 ±0.15	26.0±2.2	2.5—8	22
H	1.35±0.15		1.6—50	36
	1.78±0.35		1.23—10	35
	1.62±0.20		8—100	22
	1.82±0.19		5—17	37
	1.5 ±0.3		2.6—50	14
	1.66±0.21	11.3±4.7	2.5—8	16
	1.60±0.15	11.9±2.0	2.5—8	22
	1.59±0.15		2.5—8	5
Total flux (the energy interval is indicated in Bev per particle)	1.7 ÷1.8	—	10—50	9
	1.5	8800	10^2—10^4	38
	1.53±0.20		15—$2 \cdot 10^6$	39
	2.13	$1.39 \cdot 10^7$	$4 \cdot 10^6$—10^9	40
	2.17±0.10	$8.7 \cdot 10^6$	$5 \cdot 10^6$—10^9	41
	1.5 ±0.1		$8 \cdot 10^5$—$8 \cdot 10^6$	42
	2.2 ±0.3		$8 \cdot 10^6$—$3 \cdot 10^7$	
	1.5 ±0.2		10^8—10^9	

$$I_A(>\varepsilon) = K_A \varepsilon^{-\gamma+1}, \qquad (1.1)$$

where $I_A(>\epsilon)$ is the flux (particle/m^2 sr-sec) of nuclei of group A with total energy per nucleon greater than ϵ (in Bev). The values of K_A and γ are given in Table II. It is very important that the spectrum exponent γ has the same value, $\gamma = 2.5 \pm 0.2$, within the limits of measurement accuracy, for different cosmic-ray charge groups. The statement made that nuclei with different Z have different spectra (see reference 26) has not been confirmed by later data. We note that even if the VH subgroup of very heavy nuclei is separated, its spectrum remains similar to the spectrum of the remaining groups.[5,22]

In the low-energy region (kinetic energy $\epsilon_k < 1$ Bev/nucleon) the spectrum of primary particles changes noticeably and is subject to strong temporal variations. The measured values of the flux of α particles in this region are given in references 6, 8, 12, 27, and 28. According to these data, the flux of α particles increases with increasing energy up to $\epsilon_k \sim 400$ Mev/nucleon. The differential energy spectrum has a maximum near $\epsilon_k = 400$ Mev/nucleon,[12,27,28] and drops off rapidly towards the lower energies. The influence of solar activity manifests itself here apparently only in the value of the maximum (which during the maximum of solar activity is reduced to less than one-half of the value during minimum activity), but not in its position. The maximum in the differential spectrum ("high-latitude cutoff") is located[6,29] at the same value of energy per nucleon for all nuclei with $Z \geq 2$.

The fact that the cutoff energy is independent of the nuclear charge precludes the possibility of attributing the high-latitude cutoff to ionization losses of cosmic-ray particles in interstellar space or in the region adjacent to the sun. Consequently, either there are no low-energy particles in the primary cosmic radiation at all (that is, the cosmic ray sources do not produce such particles), or else they are "cut off" by the magnetic field of the solar system. If the low-energy cutoff is produced by the magnetic field, then the maximum of the differential spectrum should occur, for all particles, at the same value of the magnetic rigidity p/Z (in billions of volts), where p is the particle momentum in Bev/c. From this point of view, information on the behavior of the proton spectrum in the low-energy region is particularly important. Unfortunately, measurements of the proton spectrum in the low-energy region are greatly hindered by the effect of the albedo and by strong temporal variations. An analysis[31] and a summary of the data[5] show that, at least during the time of maximum solar activity, the integral spectrum of the protons continues to increase with decreasing energy, down to $\epsilon_k \simeq 1$ Bev, that is, to a rigidity $\simeq 1.8$ Bv. Particles with $A = 2Z$ have this value of rigidity at $\epsilon_k \simeq 0.3$ Bev/nucleon, i.e., near the maximum of the differential spectrum. According to references 43 and 44, the primary cosmic-ray flux continues to increase during the minimum of solar activity even with further reduction in energy. This would mean that the maximum of the proton differential spectrum, if it does exist, is located at a different (lower) value of rigidity than that of the heavier particles. Yet according to reference 45 the proton and α-particle spectra are of the same order of rigidity, down to 1 Bv, particularly during the minimum period. Since the data of reference 45 were obtained during increased solar activity, the contradiction may be only illusory. A solution of this problem calls for regular measurements during the cycle of solar activity.

Without dwelling in detail on the interpretation of the high-latitude cutoff (see references 26, 46, and 47), we note merely that both in cutoff by the ordered magnetic field of the solar system,[48,49] and in a spectrum cutoff due to a scattering by random fields in the solar system,[50] *a shift would be expected in the differential-spectrum maximum* during the course of the eleven-year cycle (see Note Added in Proof, I). Consequently, if the invariance of the position of the maximum is confirmed it may be necessary to seek the cause of high-latitude cutoff in the cosmic-ray sources (when the influence of solar activity would reduce merely to modulation of the cosmic-ray intensity). *This implies the following possibilities:*

1. All particles are cut off at the same rigidity. Then all the protons are primary (they are accelerated in the sources) and the change of the composition along the path from the source is insignificant.

2. The cutoff occurs at the same energy per nucleon, i.e., it occurs at half the rigidity for protons as for nuclei with $Z \geq 2$. Such a cutoff can result either from the specific properties of the source, or from the secondary nature of the protons in the cosmic rays (see Sec. 4). In the latter case the proton maximum may spread out considerably through loss of some of the energy to fragmentation in the meson component.

It must be noted that the choice between these possibilities is made difficult by the presence of cosmic rays of solar origin, which make a substantial and extremely irregular contribution to the considered region of low-energy cosmic rays (see reference 51 concerning solar cosmic rays). See also Noted Added in Proof, II.

In the region of very large energies, $E > 10^5$ Bev $= 10^{14}$ ev, *it is practically impossible to observe individual primary particles directly*, in view of the small flux of particles with such energies. Thus, according to reference 39, the flux of particles with energy greater than 2×10^{15} ev amounts to $I(E > 2 \times 10^{15}\text{ ev}) = 3.6 \times 10^{-6}$ particle/m^2 sr-sec $= 1.3 \times 10^{-2}$ particle/m^2 sr-hr. Even if the detector has an effective area of 1 square meter, hundreds of flight hours at high altitudes are necessary to "catch" at least one such particle, not to speak of the difficulty of identifying this particle. Our information concerning the primary cosmic radiation at energies greater than 10^{14} ev are based entirely on results of investigations of extensive atmospheric showers.

At the present time, the interpretation of the processes that occur in extensive atmospheric showers still does not lead to unequivocable conclusions concerning the properties of primary particles that produce these showers. One must therefore treat cautiously any conclusions pertaining to the composition, energy spectrum, and maximum energy of primary high-energy particles. *It is important to bear in mind* that the primary-particle energy spectrum observed in the energy region of extensive atmospheric showers is no longer referred to the energy per nucleon, *but to the total energy of the particle producing the shower.* Whereas the main fraction of cosmic rays with energies per nucleon greater than a specified value is made up of protons, this is not at all the case for the flux of particles with a specified value of total energy. In fact, we can readily obtain from the spectrum (1.1), referred to the energy per nucleon, the following spectrum referred to the total energy per particle

TABLE III

Group of nuclei	A	$A^{1.5}$	$\frac{I_A(>E)}{I_p(>E)}$
p	1	1	1
α	4	8	0.54
L	10	32	0.05
M	14	53	0.23
H	31	173	0.33
VH	51	365	0.20

$$I_A(>E) = K_A\left(\frac{E}{A}\right)^{-\gamma+1} = \frac{K_A A^{\gamma-1}}{E^{\gamma-1}}. \quad (1.2)$$

Table III lists the number of nuclei per proton, from different charge groups, in the flux of particles with energy greater than specified value. We assume here that the spectrum has the same index, $\gamma = 2.5$, for all groups and use the relative compositon as given in Table I.

Table III shows that more than half of all the cosmic-ray particles with energies greater than a specified value is made up of nuclei with $Z \geq 2$. If the spectrum is steeper, the fraction of these nuclei will be even greater. Naturally, we can extend these results toward the energies of extensive atmospheric showers only if we assume that the spectra of all the charge components remain similar. According to references 34 and 22, this is true at least up to $\sim 10^{12}$ ev. There are also data, obtained with the aid of emulsions, which indicate that the composition is constant even at higher energies (see, for example, reference 33). In addition, the spectrum of the total flux *of cosmic rays has apparently no singularities at all* in the energy region $\lesssim 10^{15}$ ev. It is therefore natural to expect the composition of the cosmic rays, and consequently also the spectra of the individual components, to remain unchanged on going over into the region of extensive atmospheric showers. This would mean that more than half of the showers with a given energy is produced not by protons, but by heavier nuclei, with $1/A$ the value of energy per nucleon.[52] An experimental verification of this statement is being undertaken (see reference 53).

The picture in the region of still higher energies, $E > 10^{15}$ ev, is still insufficiently clear. Thus, according to reference 41, the spectrum remains smooth and has no singularities up to the highest energies, $\sim 10^{18}$ ev (at the same time, the value of γ increases at high energies to $\gamma = 3.17$ at $5 \times 10^{15} < E < 10^{18}$). To the contrary, it is stated in reference 42 that the slope of the spectrum changes in the region $E \simeq 10^{16}$. It is assumed also in reference 52 that the slope of the spectrum has a singularity at $E \simeq 10^{15}$ ev. The following possible reasons for this singularity have been discussed:

1) Change in the character of the elementary act in the region of ultra-high energies.[54] In this case, a revision of the procedure used to determine the energy of the primary particles is necessary, and the existing determinations of the spectrum at energies greater than 10^{16} ev would be invalid.

2) Change in the conditions of emergence of the particles from the galaxy at $E \gtrsim 10^{16}$ ev. In this case particles with $E > 10^{16}$ could be essentially of metagalactic origin (see Sec. 3c and reference 42).

3) Existence of an upper limit for the hardness of cosmic rays, generated by the most intense sources in the galaxy, while the chemical composition remains constant over the entire range of hardness.[52] In this case, since nuclei with different values of A have different energies at the same value of hardness, there will be no sharp boundary in the spectrum of extensive atmospheric showers. Thus, iron nuclei will be cut off at an energy $A/2 = 28$ times greater than protons. A smooth matching of the spectrum of the main source with the spectrum of the less intense sources, which produce particles of greater hardness, is possible here.

A completely analogous picture (in the presence of cutoff at a certain maximum hardness) will take place also in the case when the protons are of a secondary nature (see Sec. 4). The only difference lies in the fact that the smearing of the energy spectrum should occur in this case over twice as large a region of energy, for in this case the upper energy limit for the protons is determined not by the maximum hardness, but by the maximum energy per nucleon in the primary nuclei.

There are still no real grounds for preferring any of these possibilities. It must be kept in mind, however, that in the two former cases account must be taken of the indicated "chemical" smearing of the singularity (kink) in the spectrum, provided the composition at energies greater than 10^{15} ev does not differ from that known at lower energies as regards reduction in the fraction of the heavy nuclei.*

Of great importance to the theory of the origin of cosmic rays is also the question of the maximum particle energy encountered. The observed spectrum of extensive atmospheric showers extends to the region $E > 10^{17}$ ev, and according to references 41 and 55, up to $\sim 10^{19}$ ev. Such energies can still be reconciled with the theory of galactic origin of cosmic rays, provided that the particles with the greatest energies are the heavy nuclei. On the other hand, if it is the primary protons that have the energy $\sim 10^{19}$ ev, as is assumed in reference 55, one can apparently conclude that the ultra-high-energy particles are of extragalactic nature (see Secs. 3c and 3d).

*It must be emphasized, in addition, that any assumption regarding the change in the character of the elementary act will remain utterly unfounded until it is proved that the investigated showers are produced by protons.

Let us note, finally, that the new measurements, like the earlier ones, have disclosed no anisotropy whatever, connected with either the galaxy or the metagalaxy, of the primary cosmic radiation. Thus, a thorough analysis was made in reference 41 of the "suspected" directions, the galactic plane and the axis of the spiral arm. Within the limits of statistical errors, which amount to 1% for an energy of $\sim 4 \times 10^{14}$ ev, the primary radiation was found to be isotropic. According to reference 55, the anisotropy, if it does exist, does not exceed the measurement accuracy, 1% at $E \lesssim 10^{16}$ ev and 3% at $E \lesssim 10^{17}$ ev. Thus, cosmic radiation is isotropic even at very high energies [the figures given here are the values of $\delta = (I_{max} - I_{min})/(I_{max} + I_{min})$, where I_{max} and I_{min} are the maximum and minimum values of the flux].

We did not concern ourselves here with the soft component of the primary cosmic rays at the earth's surface, since there are no data more recent than reference 1 on the electrons and positrons. We note merely that estimates have been recently published[56,57] of the possible amount of γ rays produced in cosmic-ray sources by α and β decay of unstable nuclei, by synchrotron radiation, and by collision of high-energy particles.

2. RADIO-ASTRONOMICAL DATA

a) Magnetic Bremsstrahlung (Synchrotron Radiation)

By measuring the intensity and frequency spectrum of cosmic radio waves, it is possible to determine, under certain assumptions, the concentration and the energy spectrum of relativistic electrons (and positrons), which make up the electron component of cosmic rays. This question was considered in detail in reference 1 and in references 2, 3, and 58 — 62. We shall make here only a few remarks and repeat, for convenience, the formula for the intensity of radio radiation

$$I_\nu \equiv \frac{2k\nu^2}{c^2} T_{\text{eff}} = \frac{R}{4\pi} \int_0^\infty P(\nu, E)\, N_e(E)\, dE$$

$$\approx 1.3 \cdot 10^{-22} (2{,}8 \cdot 10^8)^{\frac{\gamma-1}{2}} U(\gamma) K R H_\perp^{\frac{\gamma+1}{2}} \lambda^{\frac{\gamma-1}{2}} \frac{\text{erg}}{\text{cm}^2\ \text{sec-cps-sr}}. \quad (2.1)$$

here $\lambda = c/\nu$ is the wavelength, k is Boltzmann's constant, T_{eff} is the effective temperature, $H_\perp$ the component of the field **H** perpendicular to the line of sight, and $U(\gamma)$ a function of γ, the value of which, for example, is 0.087 when $\gamma = 3$ and 0.125 when $\gamma = 2$. It is assumed in (2.1) that the electrons have along the entire path R the following differential spectrum

$$N_e(E) = KE^{-\gamma}. \tag{2.2}$$

A radio spectrum with a distribution (2.2) is independent of $H_\perp$ and is determined only by the exponent γ, with

$$I_\nu \propto \lambda^\alpha \propto \nu^{-\alpha}; \quad \alpha = \frac{\gamma-1}{2} \quad \gamma = 2\alpha + 1. \tag{2.3}$$

In the case of thermal radio emission from a medium with temperature T ($h\nu \ll kT$)

$$I_\nu = \frac{2k\nu^2}{c^2} T_{\text{eff}}, \quad T_{\text{eff}} = T(1 - e^{-\tau}). \tag{2.4}$$

Here $\tau = \int \mu\, ds$ is the optical thickness (μ is the coefficient of absorbtion and ds is the element of the ray trajectory). In the interstellar plasma (see, for example, reference 63, Sec. 37, where N is the electron concentration in the plasma):

$$\mu = \frac{10^{-2} N^2}{T^{3/2} \nu^2} \left[19.8 + \ln \frac{T^{3/2}}{\nu} \right]. \tag{2.5}$$

It is clear from (2.4) and (2.5) that for a thick layer ($\tau \gg 1$) we have $I_\nu \sim \nu^2$ and $T_{eff} \simeq T$, while for a thin layer ($\tau \ll 1$) $I_\nu \sim$ const and $T_{eff} \sim \nu^2$. At the same time, for the nonthermal emission from the galaxy and from different discrete sources, usually $I_\nu \sim \nu^{-\alpha}$, where $0.4 \lesssim \alpha \lesssim 2$, i.e., $T_{eff} \sim \nu^{-(\alpha+2)} = \nu^{-(2.4 \text{ to } 4)}$. It is clear therefore that the thermal component of the radio emission can be reliably separated by performing the measurement at several frequencies, so that the spectrum of the magnetic bremsstrahlung can be determined.

We recall also that the ultrarelativistic electron ($E \gg mc^2$) radiates almost exclusively in the direction of its velocity* and the only radiation received on earth is that from particles that move for some time along the line of sight. Furthermore, magnetic bremsstrahlung is strongly polarized.[59,65–73] Thus, for example, for electrons with isotropic direction distribution and with a spectrum of the form (2.2), the polarization $(I_{max} - I_{min})/(I_{max} + I_{min})$ amounts to[68,69] 75% when $\gamma = 3$ and 69% when $\gamma = 2$. In this case the preferred direction of oscillation of the electric vector of the received radiation coincides with the direction of acceleration, i.e., it is simultaneously perpendicular to the velocity of the particle (line of sight) and to the field vector **H**. For an inhomogeneous field, naturally, the polarization is averaged. In addition, an important factor at radio frequencies is the rotation of the plane of polarization in the interstellar ionized gas.[67,70] This effect greatly reduces the degree of polarization, particularly in the range of meter waves. Nevertheless, a weak polarization of the overall galactic radio radiation has apparently been observed in this band.[71,72] In the case of the Crab Nebula, polarization was observed of both the optical magnetic bremsstrahlung and of the radio emission in the centimeter band.[72a,b]

*We refer here to radiation in vacuum. See reference 59 regarding the role of the medium; in the cases of interest to us, the effect of the medium is quite small. In vacuum the radiation is concentrated in an angle $\theta \sim mc^2/E$ about the velocity direction; even at $E \sim 5 \times 10^8$ ev the angle amounts to several minutes.

b) Certain Results of Observations and their Interpretation (Structure of the Galaxy, Discrete Sources)

The radioastronomical data of interest to us concern the spatial distribution, intensity, and spectrum of non-thermal radio emission from the galaxy, galactic nebulae, and extragalactic objects (galaxies, clusters of galaxies, and intergalactic medium). Referring the reader to the relevant sources (see references 1, 58, 59, 66, 70 – 97), we shall dwell only on factors which are important in what follows.

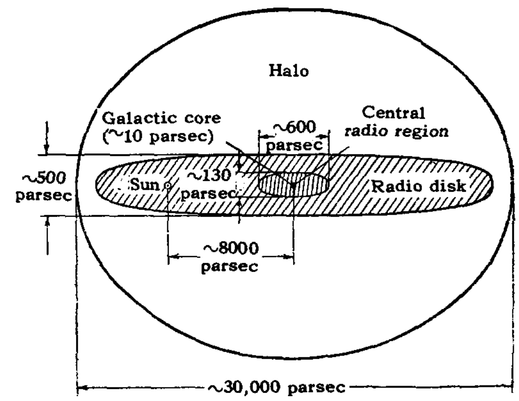

FIG. 1

The use of antennas with a high degree of directivity has permitted a substantial refinement and detailing of the information on the overall non-thermal galactic radio emission (we have in mind, first of all, measurements[77–78] at 22-cm and 3.5-m wavelengths with angular resolution on the order of 1°). At the present time we can separate three main spatial radiation regions.

1. The galactic "halo" or "corona," which has a quasi-spherical form with mean radius R* on the order of 10 or 15 kiloparsec, ≈ 3 to 5×10^{22} cm (Fig. 1). Within the measurement accuracy attained and, principally, within the degree of reliability of separating the metagalactic component, the halo can also be considered to be an ellipsoid of revolution with an axis ratio of 1.5 (see reference 75, p. 431). The volume of the halo is $V \sim 1$ to 5×10^{68} cm^3. The greater part ($\sim 80 - 90\%$) of all the cosmic radio emission originates in the halo. A distinguishing feature of the radio emission from the halo is the weak dependence of its intensity on the direction, and also on the distance to the galactic center.

2. The "radio disk" of the galaxy is a region where the intensity of the radio emission is much higher than in the halo, and where it diminishes rather sharply with increasing distance from the galactic plane. The thick-

*Most latest estimates[75,89] lead to a value $R \simeq 10$ kiloparsec for the average radius, hence $V \simeq 10^{68}$ cm^3.

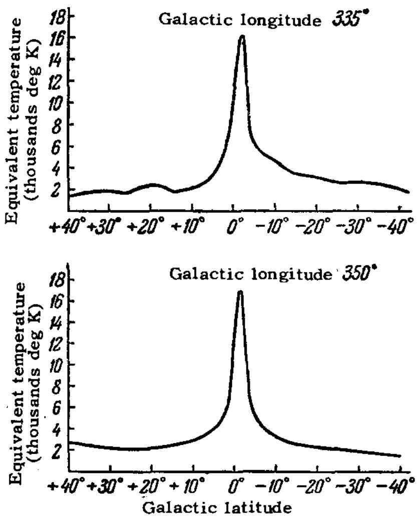

FIG. 2

ness of the radio disk is ~ 500 parsec = 1.5×10^{21} cm, whereas the thickness of the flat system of interstellar gas clouds and of the optical spiral (this region can be called the optical disk) amounts to ~ 250 parsec. The character of the transition from the radio disk to the halo is clearly illustrated in Fig. 2, where the effective temperature of the radio emission T_{eff} at 3.5 m is shown as a function of the galactic latitude for two galactic longitudes.[78] There are definite indications (reference 75, p. 431) that the radio disk contains a spiral structure, such that the "radio spiral" includes so to speak the optical spiral, which is one-half or one-third as thick. The entire emission from the "disk" at 3.5 m is approximately one-fifteenth the intensity of the total radiation of the "halo."

3. The "central radio region" of the galaxy is the region surrounding the galactic center (core). The dimensions of the non-thermal source contained there, assuming it to be an ellipsoid of revolution, are approximately 300 parsec (major axis) and 130 parsec (minor axis).[77,90] From radio observations of the neutral hydrogen line (λ = 21 cm) it has been found most recently[84,84a] that this non-thermal source lies in the central part of the neutral hydrogen region (major axis ~ 600 — 700 parsec, minor axis ~ 100 — 130 parsec) with a concentration (averaged over the entire region) $\bar{n} \sim 1$ or 2 cm^{-3}. This entire mass of neutral hydrogen, and obviously the stars contained in this region (their concentration is 500 to 1000 times smaller than in the vicinity of the sun) rotate rapidly (speed ~ 200 km/sec at ~ 100 parsec from the center). In the central part of the neutral-hydrogen cloud, a galactic core was observed[85-87] with dimensions ~ 10 parsec; an analogous core is found, for example, in the M31 Nebula (Andromeda). The cores contain polarized hydrogen and are thermal sources of radio emission. In the center of the core of the galaxy, which naturally does not have sharp boundaries, the concentration reaches $\bar{n} \sim 10^3\,cm^{-3}$.

FIG. 3

Measurements in the line of neutral hydrogen have led, in addition to the disclosure of a central rotating region, also to substantial progress with respect to ascertaining the position of the arms of the galactic spiral.[94,84] The overall picture is clear from Fig. 3, where the cross denotes the galactic center; the circle with a dot in the center denotes the solar system, and the light bands correspond to observed clusters of neutral hydrogen (it must be borne in mind that the region on the line and near the line drawn from the sun to the center could not be investigated). It follows from Fig. 3 and from a more complete analysis of the data, that the arms of the spiral are formed only at distances on the order of 3000 parsec from the center (the distance from the sun to the center is 8200 parsec). There is a sufficiently large number of individual arms, and they are apparently quite short in many cases, and are also inhomogeneous along their axis with respect to thickness and gas density (see, in particular, reference 84a).

Let us make a few remarks concerning the character of the galactic magnetic field. It is usually assumed that the magnetic field in the arms of the optical spiral is ordered to a considerable degree. This conclusion is based on information on the polarization of the light from the stars, which is attributed to the passage of rays through a layer of dust particles which are oriented in a magnetic field. An analysis of the shape of many galactic nebulae (works of G. A. Shaĭn and others, see reference 87) leads to similar results. All these data, however, refer only to a certain average field, the averaging being carried out over a rather large region. The existence of such an ordered average field is apparently fully compatible with the presence in the spiral of random, disordered fields. It is particularly important that the radio-astronomical observations are evidence that the field in the spiral is far from regular. Actually, if an observer is located in a region with a homogeneous field, the intensity of the magnetic bremsstrahlung in the direction of the field will be equal to zero. Yet in the direction of the arms of the spiral (particularly in the direction of the arm that contains the sun), the radio emission not only does not vanish, but, to the contrary, increases (see reference 75, p. 431). It is precisely in this manner that the presence of a spiral structure of the "radio disk" of the galaxy was explained. When these results by Mills are confirmed (in particular, measurements are needed at different wave lengths with different angular resolutions), no doubt will apparently remain of the existence of a sufficiently strong disordered field in the arms of the spiral. The same problem concerning the character of the field in the arms is connected with the problem of the nature of the bright "radio belt" — a region of increased radio emission, in the form of a circle on the celestial sphere. In reference 93 this radio belt is connected precisely with the existence of a regular field in the arm. If the field in the arm that contains the sun is regular (quasi-periodic), then the magnetic bremsstrahlung will be particularly strong for particles that move perpendicular to the field. Specifically, if the velocity distribution of the radiating electrons is isotropic, the intensity will be proportional to $H_\perp^{(\gamma+1)/2} \sim (\sin\theta)^{(\gamma+1)/2}$, where θ is the angle between the field (axis of the arm) and the line of sight. If $\gamma = 2.4$ [$\alpha = (\gamma-1)/2 = 0.7$] in an homogeneous field, and if the particle distribution is isotropic, the radiation power at an angle $\theta = 30°$ is 3.3 times smaller than the radiation power at $\theta = 90°$. The observed independence of the radio brightness on θ is steeper; it is therefore necessary to assume further that the electrons are not isotropically distributed by velocity. This last assumption is doubtful and, in particular, is not in agreement with the available information on the isotropy of cosmic rays. Furthermore, the axis of the "radio belt" does not coincide with the direction of the ordered field in the arm, obtained from other data (see reference 95 and reference 75, p. 571). Finally, the hypothesis discussed here regarding the nature of the "radio belt" is decisively in contradiction with the conclusion drawn earlier (also based on radio observations) that there is also radiation along the arms and, in general, that a strong disordered component of the field exists in the arms. We can thus think that the "radio belt" is more likely to be a halo structure, i.e., it indicates that the halo contains certain large-scale irregularities of the magnetic field.

The cosmic rays on earth are highly isotropic (see Sec. 1b) and this isotropy, at least as regards the high-energy particles, cannot be considered local (see Sec. 3c). We can conclude even from this that the cosmic rays enter the arms quite freely from both ends, and perhaps also from the sides. Such an assumption is particularly natural if it is considered that there are

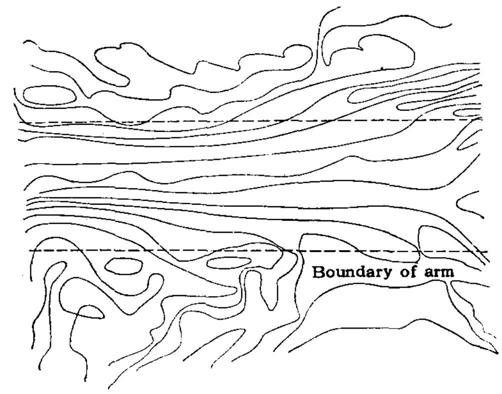

FIG. 4.

many arms, that they are relatively short, and that they are so to speak "imbedded" in a tremendous reservoir of cosmic rays, the halo. It is necessary to take furthermore into account the noted broadening of the radio disk, compared with the optical disk. Two causes are possible here. It can be assumed first that the concentration of the radiating electrons is higher in the optical arms than in the halo, and that the electrons diffuse from the arms into the halo. In other words, the broadening of the radio disk can be attributed to a gradual variation of the electron concentration.[91] But in this case the electrons should be able to leave through the walls of the arms. Orderliness or even quasi-homogeneity of the field in the arms are compatible, at least in principle, with such a picture. Actually, an ordered field can be accompanied by large scattering (outflow) of magnetic flux from the arm (see, for example, Fig. 4, in which the field in the arm itself is assumed, for simplicity, to be quasi-homogeneous). Another possible cause of the broadening of the radio disk is connected with the attenuation of the magnetic field as it passes from the spiral to the halo (frequently, for example, one assumes for these regions the values $H = 7 \times 10^{-6}$ and $H = 2$ or 3×10^{-6} oe). Even if the concentration of the relativistic electrons is constant, the intensity will decrease as $H_\perp^{(\gamma+1)/2} \simeq H_\perp^{1.7 \text{ to } 1.8}$. When $H_\perp$ is reduced to one-third and $\gamma = 2.6$, the intensity decreases by approximately 7 times. A reduction of $H_\perp$ to one-half, which appears to be more realistic, causes the intensity to change by a factor of 3.3 at $\gamma = 2.4$.* At the same time, on going from the disk to the halo, the intensity decreases by a factor of 9 or 10 (see Fig. 2). Actually, a certain decrease in concentration and a decrease in the field upon transition to the halo probably play a certain

*We disregard here the possibility of conservation of the adiabatic invariant on going from the radio disk to the halo.[96] The question of the rate of change of the invariant in the galaxy is still not clear (see Sec. 3c); if the invariant is conserved, $\sin^2\theta/H = \text{const}$ and a reduction in the field by one-half results in

$$H_\perp^{\frac{\gamma+1}{2}} = H^{\frac{\gamma+1}{2}} (\sin\theta)^{\frac{\gamma+1}{2}} \sim H^{\frac{3(\gamma+1)}{4}},$$

that is, a reduction by approximately a factor of 6.

role, too. The important fact, from the point of view of the question under consideration, is that even a constant concentration of cosmic rays in the spiral and in the halo would in itself be a very weighty argument in favor of the existence of a close connection between the cosmic rays in both regions (in the absence of such a connection we expect a sharp difference in concentration between the halo and the disk). We can thus conclude from the radio observations either that the walls of the optical spiral are transparent to cosmic rays, or, in any case, that there is great freedom of exchange of cosmic rays between the halo and the spiral. This means that the arms differ little from the regions in the halo and, for example, while regions with a quasi-homogeneous field are characterized by a single dimension $\lesssim 100$ parsec (see Sec. 3c), the arms are elongated regions $d \sim 250$ parsec thick and $L \sim (1 \text{ to } 10) \times 10^3$ parsec long. If the cosmic rays are isotropic in the halo, such a model leads us to expect isotropy in the distribution of the directions of cosmic rays in the spiral, too.*

Returning to the general non-thermal galactic radio emission, we note that, within the accuracy attained, its spectrum is approximately the same in the halo, in the radio disk, and in the central radio region; this is natural if a fast exchange of cosmic rays between these regions is assumed. In references 58 and 1, a value $\alpha = 0.82$ $(\gamma = 2.64)$ was assumed for this case, while reference 77 uses, on the average, $\alpha = 0.70 \pm 0.1$ $(\gamma = 2.4 \pm 0.2)$. Other values are also encountered,[83] and the measurement accuracy is undoubtedly still inadequate (the difficulty lies in the need for comparing the intensity at the different frequencies, using different antennas). More accurate information on the spectrum of non-thermal radio emission as a function of the galactic coordinates (in particular, for the halo, disk, and central region as a whole) remains an important and urgent problem.

The average differential energy spectrum of the electrons in the galaxy was found in reference 1 to be $N_e(E) \simeq 5 \times 10^2 E^{-2.64}$ ev^{-1} cm^{-3}, for $\alpha = 0.82$ and $H_\perp \sim 10^{-5}$ (E is in electron volts). From this we get

$$N_e(E > 10^9 \text{ev}) = \int_{10^9}^{\infty} N_e(E)\, dE \simeq 5.5 \cdot 10^{-13} \text{cm}^{-3}$$

and $N_e(E > 10^8 \text{ev}) \simeq 2.5 \cdot 10^{-11}$ cm^{-3}.

*For the radiating electrons that are formed in nuclear collisions (see Sec. 3e), a certain anisotropy may result, to be sure, from the large concentration of gas in the spiral. This causes more electrons to be produced inside the spiral than near the spiral. Those of the newly-produced electrons which have a greater velocity along the field will leave the spiral more readily, so that more electrons are left with velocities making large angles to the field (this very effect is considered in reference 93). It is assumed in such a reasoning, however, that the field in the arm is essentially ordered. If the arm contains a large disordered field component (see above), the particles cannot leave the region of the arm rapidly, and the distribution remains practically isotropic.

At the same time, on earth we have N_e $(E > 10^9$ ev$)$ $< 10^{-12}$ cm^{-3}. A value N_e $(E > 10^9$ ev$) \simeq 3 \times 10^{-13}$ cm^{-3} was obtained in reference 91 for the radio disk, using a somewhat different method, with $\alpha = 0.75$ $(\gamma = 2.5)$.

The accuracy of the foregoing estimate is low (for example, in reference 1 the value of N_e is reduced by a factor of 5, in order to account somehow for the reduced field in the halo). We can therefore say, in agreement with the foregoing statements, that the concentration of the electrons in the halo and in the disk is of the same order of magnitude and probably even closer. In the central radio region, according to reference 91, we have for $H_\perp \sim 5 \times 10^{-5}$ and $\gamma = 2.5$ a value N_e $(E > 10^9$ ev$) \simeq 1.5 \times 10^{-12}$ cm^{-3}. The total energy of the relativistic electrons is $W_e \sim 3 \times 10^{51}$ ergs in the central region (see reference 90), and $W_e \sim 10^{54}$ to 10^{55} in the entire galaxy. The last value is obtained for a halo of volume $V \sim (1 \text{ to } 5) \times 10^{68}$ cm^3 and an average electron energy density $\overline{w}_e \sim 10^{-2}$ ev/cm^3, which, according to the values of the total energy of the cosmic rays $(W \sim 10^{56}$ to 10^{57} ergs$)$ and electron energy density given below (Sec. 3b), amounts to 1% of the total energy density of the cosmic rays.

Let us discuss briefly the magnetic bremsstrahlung from discrete sources — galactic nebulae and galaxies. Certain pertinent calculations and their results are given in reference 1. We mention first the determination of the spectrum of the sources (see reference 75, page 297). For galactic sources, on the average, $\overline{\alpha} = 0.6$ and the dispersion is high (values are encountered from $\alpha = 0.2$ to $\alpha = 1.4$, although in most cases $0.4 \leq \alpha \leq 0.8$). For extragalactic sources, on the average, $\overline{\alpha} = 0.9$ $(0.4 \leq \alpha \leq 1.6$, but in the main $0.6 \leq \alpha \leq 1.0)$. Finally, for unidentified sources (essentially extragalactic objects), $\overline{\alpha} = 1.2$, and values up to $\overline{\alpha} = 2.2$ are encountered.* The power-law character of the spectrum, that is, the possibility of choosing one value of α for a given object, is retained here over a very wide range. For example, for Cassiopeia A we have $\alpha = 0.80$ in the interval $3 \times 10^7 \leq \nu \leq 10^9$ cps.

As regards the power of the individual sources, we confine ourselves essentially to the results of reference 97, listed in Table IV. The calculations have been made under two assumptions. In the first (3rd column of the table) the energy of the magnetic field in the source $\int \frac{H^2}{8\pi} dV = \frac{\overline{H^2}}{8\pi} V$ is assumed to be equal to the energy of the radiating electrons (and positrons). The corresponding value of the average field is indicated in column 4. In the second case, the energy of the magnetic field is assumed equal to the energy of all the cosmic rays in the source, and is 100 times greater than the energy of the electrons (see column

*In an earlier paper by the same author[76] values $\overline{\alpha} = 0.74$ (instead of 0.6) and $\overline{\alpha} = 1.05$ (instead of 0.9) are given. This also shows the degree of inaccuracy in the available data.

TABLE IV

Source	Radiated power (magnetic bremsstrahlung mechanism), erg/sec	Total energy (energy of the electrons and the magnetic field), erg	Average value of the field, oe	Total energy (energy of the protons and of the magnetic field), erg	Average value of the field, oe
		Power of galactic sources			
Crab Nebula (A Tauri)	Radio emission – 8×10^{33} Optical radiation – 10^{36}	$\sim10^{48}$	$\sim10^{-3}$—10^{-4}	$\sim10^{50}$	10^{-2} (as indicated in the text, this value is highly exaggerated)
A Cassiopeiae	$2.6\cdot10^{35}$	$4.1\cdot10^{48}$	$2\cdot10^{-4}$	$5.7\cdot10^{49}$	10^{-3}
IC 443	$4\cdot10^{33}$	$8\cdot10^{48}$	10^{-5}	$1.2\cdot10^{50}$	$4\cdot10^{-5}$
Filamentary nebula in Cygnus	$2.5\cdot10^{32}$	Electrons – 3×10^{46}, magnetic field – 10^{50}		Protons – 3×10^{48}, magnetic field – 10^{50}	$5\cdot10^{-5}$
Central radio region of the galaxy	$1.4\cdot10^{38}$	$1.0\cdot10^{52}$	10^{-5}	$1.3\cdot10^{53}$	$4\cdot10^{-5}$
		Power of the galaxies and other extragalactic sources			
Galaxy	$\sim10^{38}$	$\sim3\cdot10^{54}$ (electrons) $\sim10^{56}$ (magnetic field)		$\sim3\cdot10^{56}$	$7\cdot10^{-6}$ (disk) $2\cdot10^{-6}$ (halo)
*M*31 (Andromeda)	$1.9\cdot10^{38}$	$2.1\cdot10^{55}$	$8\cdot10^{-7}$	$3.0\cdot10^{56}$	$3\cdot10^{-6}$
Magellanian clouds	$1.3\cdot10^{37}$	$2.5\cdot10^{54}$	$1\cdot10^{-6}$	$3.4\cdot10^{55}$	$4\cdot10^{-6}$
NGC 4038—39	$2.1\cdot10^{39}$	$1.7\cdot10^{56}$	$2\cdot10^{-6}$	$2.3\cdot10^{57}$	$7\cdot10^{-6}$
NGC 1068	$7.5\cdot10^{39}$	$3.2\cdot10^{55}$	$2\cdot10^{-5}$	$3.6\cdot10^{55}$	$6\cdot10^{-5}$
NGC 5128 (A Centauri) Central region	$2.4\cdot10^{41}$	$3.2\cdot10^{56}$	$2\cdot10^{-5}$	$4.4\cdot10^{57}$	$9\cdot10^{-5}$
NGC 5128 Halo	$2.2\cdot10^{41}$	$5.0\cdot10^{58}$	$1\cdot10^{-6}$	$7.0\cdot10^{59}$	$5\cdot10^{-6}$
NGC 1316 (A Fornacis) Central region	$8\cdot10^{40}$	$2.1\cdot10^{56}$	$2\cdot10^{-5}$	$3.0\cdot10^{57}$	$6\cdot10^{-5}$
NGC 1316 Halo	$1.6\cdot10^{41}$	$1.8\cdot10^{58}$	$1\cdot10^{-6}$	$3.2\cdot10^{59}$	$5\cdot10^{-6}$
NGC 4486 (A Virginis) Peak	$2.3\cdot10^{42}$	$1.7\cdot10^{54}$	$2\cdot10^{-4}$	$2.4\cdot10^{55}$	$7\cdot10^{-4}$
NGC 4486 Central radio source	$3.5\cdot10^{41}$	$1.7\cdot10^{57}$	$1\cdot10^{-5}$	$2.4\cdot10^{58}$	$4\cdot10^{-5}$
NGC 1275	$6.4\cdot10^{41}$	$9.4\cdot10^{56}$	$2\cdot10^{-5}$	$1.3\cdot10^{58}$	$8\cdot10^{-5}$
NGC 6166	$7.8\cdot10^{42}$	$1.4\cdot10^{57}$	$3\cdot10^{-5}$	$1.9\cdot10^{58}$	$1\cdot10^{-4}$
A Hydrae	$1.5\cdot10^{43}$	$1.0\cdot10^{58}$	$8\cdot10^{-5}$	$1.5\cdot10^{59}$	$3\cdot10^{-4}$
A Cygni	$5.7\cdot10^{44}$	$2.8\cdot10^{59}$	$4\cdot10^{-5}$	$3.9\cdot10^{60}$	$2\cdot10^{-4}$
Galaxy cluster in Coma	$1.0\cdot10^{41}$	$2.9\cdot10^{59}$	$2\cdot10^{-7}$	$4\cdot10^{60}$	$7\cdot10^{-6}$

5; the corresponding value of the field is indicated in column 6). It is probable that in most cases the second assumption is much closer to reality. The assumption that the magnetic energy equals the energy of the cosmic rays corresponds to conditions when the total energy is close to minimum.* Therefore Table IV actually indicates the minimum values of the energy. In the calculation of the energy it is necessary to know the dimension of the source and the distance from it; in addition, it is assumed somewhat arbitrarily that there is little or no radio emission when $\nu > 10^{10}$ and $\nu < 10^7$ cps. Thus, the values listed in Table IV are in most cases plainly tentative.

Taking this stipulation into account and assuming that the total energy of the cosmic rays is 100 times greater than the energy of the electrons, the latter is equal to the values given in column 5 of Table IV, divided by 200.

The galactic nebulae are sources of strong magnetic bremsstrahlung and are shells of supernovae. Thus, the Crab Nebula (A Tauri) is the supernova of 1054 A.D. (field intensity, according to various estimates, is on the order of 10^{-3} to 10^{-4} and the value $H \sim 10^{-2}$ in Table IV does not seem applicable); A Cassiopeiae was assumed in reference 58 to be the supernova of 369 A.D., but according to the later data (reference 75, p. 315), this star flared up only approximately 250 years ago; the rate of expansion of the shell of this supernova exceeds 7000 km/sec.† The filamentary nebula in Cygnus is the shell of a supernova, which flared up approximately 10^5 years ago. Certain other extended shells (IC 443, A Puppis, X, Y, and Z Velae, the filamentary nebula in Auriga; see reference 91). All these extended shells and A Cassiopeiae are remnants of supernovae of the second type, which are concentrated in the galactic plane and belong at the same time to the first type of the star population of the galaxy (flat subsystem). To the contrary, radio sources connected with the envelopes of the supernovae of 1054 A.D. (Crab Nebula), 1572 A.D. (Tycho supernova) and 1604 A.D. (Kepler supernova) belong to the galactic population of the second type (spherical subsystem), which is concentrated toward the galactic center. The corresponding supernovae are the so-called supernovae of the first type. In our galaxy supernovae of the second type flare up on the average once every 50 years, while supernovae of the second type are perhaps somewhat rarer, once every 100 or 200 years.* From the frequency of the flares and from the lifetimes of the shells it follows that in principle one can observe many remnants of supernovae — on the order of 1000 (see article by G. G. Getmantsev in reference 67, p. 468). The majority of these sources almost merge with the background, and they are a very weak object in the optical part of the spectrum. Therefore, at least at the present time, there is still no contradiction between the number of observed shells and the given estimate (see reference 75, p. 315). Inasmuch as there are particularly many supernovae of the first type in the central region, it is probably they which supply the cosmic rays to this region, causing the increased concentration of cosmic rays compared with the disk and the halo (see reference 91 for more details). With respect to the extragalactic sources, it must be borne in mind that Table IV lists essentially the most outstanding and strongest of these. For "normal" galaxies, estimates lead to values which are close to or less than the energy of the cosmic rays in the galaxy ($W \sim 10^{56} - 10^{57}$; see below and Table IV). "Anomalous" objects, with singularities in their spectrum (for example, A Virginis) or in their power (for example, A Cygni or the cluster in Coma) are encountered quite rarely. We still do not have enough data to determine reliably the energy contribution from the powerful sources. However, for a distance less than $\sim 10^8$ parsec, which is of importance from the point of view of the origin of cosmic rays (see Sec. 3d), we can apparently assume that the anomalous galaxies do not affect the estimate of the total energy of the cosmic rays in all the galaxies taken together.

In conclusion we note that the assumption[98] of existence of noticeable radio emission from metagalactic space (outside the galaxies) has not been confirmed.[75,80,88] This indicates that the value obtained in reference 98 for the cosmic-ray energy in the intergalactic space is in all probability much too large (see Sec. 3d).

3. LIFETIME OF COSMIC RAYS AND CHARACTER OF THEIR MOTION IN THE GALAXY AND METAGALAXY

a) Nuclear Lifetime of Cosmic Rays

One of the most important parameters of the cosmic rays in the galaxy is their lifetime, T. For protons and nuclei, the value of T is determined by two factors — nuclear collisions and escape from the system, with $1/T = 1/T_n + 1/T_e$, where T_n and T_e are

*With respect to the filamentary nebula in Cygnus, we did not use in Table IV the condition that the cosmic-ray energy be equal to the field energy, since the obtained field would be weaker than the general galactic field. We therefore assumed the higher field intensity indicated in the table. For our galaxy as a whole, the field intensity and the energy of the cosmic rays have also been chosen from independent considerations.

†I. S. Shklovskiĭ called attention to the fact that the magnetic field in the shell of A Cassiopeiae decreases with time so rapidly that the intensity of the radio waves from this source should decrease approximately 2% annually. Many other interesting conclusions concerning supernovae and their radio emission are made also in reference 92.

*These figures are not final; there are mentions in the literature of a flare-up frequency which is several times smaller.

TABLE V. Cross sections and ranges in hydrogen and in interstellar gas

Group of nuclei	$\sigma \cdot 10^{+26}$ cm²		λ_{int}, g/cm²		λ (g/cm²) absorption in interstellar gas
	hydrogen	interstellar gas	hydrogen	interstellar gas	
p	2.26	2.8	74	72	72
α	10	11.2	16.5	18	18
L	19.3	20.7	8.7	9.8	9.8
M	28	29.7	6.0	6.8	8.0
H	48	50.5	3.5	4.0	6.0
Fe(VH)	71	74.3	2.4	2.7	2.7

respectively the nuclear lifetime and the time after which the particles escape from the system (galaxy).

The nuclear lifetime $T_n = 1/\sigma\bar{n}c$, where σ is the effective cross section for the collisions under consideration, $\bar{n}$ is the average concentration of the nuclei of the medium along the path of the cosmic particle, assumed equal to the velocity of light.

The values of the interaction cross section σ and of the range $\lambda_{int} = \bar{\rho}/\sigma\bar{n}$, where $\bar{\rho}$ is the average density of the medium, are listed in Table V for different nuclei moving in hydrogen and in interstellar gas, which contains, in accordance with its cosmic abundance, 7% of helium particles. The inelastic cross section for pp collisions is taken here from reference 99. The formula $\sigma = \pi r^2$, where $r = 1.24 \times 10^{-13} A^{1/3}$ cm, which is in good agreement with the results obtained with accelerators and in the natural cosmic-ray flux (G. B. Zhdanov, private communication), has been used for the cross sections of interaction between nuclei of $Z > 2$ and hydrogen. This formula apparently gives a somewhat excessive value for α particles. We therefore use in Table V the cross section given in reference 100 for collisions between protons and α particles. The cross sections for the interaction between different nuclei and helium have been calculated from the Bradt and Peters formula[100] (see also reference 1). Column 6 of Table V gives the effective ranges for the absorbtion of nuclei of the given group in interstellar gas. These will be discussed and used in Sec. 4d.

To determine the average concentration $\bar{n}$, it is naturally important to select the averaging region. One might think (see Sec. 2b) that the cosmic rays pass quite freely from the spiral to the halo and vice versa. In addition, there are grounds for assuming, as will be discussed later on, that the cosmic rays penetrate also into the clouds of interstellar gas. We shall therefore assume now that $\bar{n}$ is simply the ratio of the entire mass of the gas in the galaxy (including the halo) to the volume of the system, $V \sim (1 \text{ to } 5) \times 10^{68}$ cm³ (see Sec. 2b). The mass of the neutral hydrogen in the galaxy without the halo, that is, near the galactic plane only, is 2.8×10^{42} (see, for example, reference 77). For a mixture of 93% hydrogen and 7% helium, we obtain therefore as a lower limit for the average density $\bar{\rho} = \frac{3.6 \times 10^{42}}{(1 \text{ to } 5) \times 10^{68}} \sim 7 \times 10^{-27}$ to 3×10^{-26} g/cm³, which corresponds to the concentration $\bar{n} \sim (3 \text{ to } 15) \times 10^{-3}$ cm⁻³. The question of the concentration of the gas in the halo is a moot one. According to reference 101, $\bar{n}_{halo} \sim 10^{-2}$ cm⁻³, but this result is obtained theoretically and, apparently, the value $\bar{n}_{halo} \sim 10^{-3}$ cm⁻³ cannot yet be categorically refuted. Thus, in reference 108, the concentration n on the boundary of the halo (at $R \simeq 15$ kiloparsec) the concentration n is assumed to be 3.6×10^{-4}, and therefore, apparently, $\bar{n}_{halo} \ll 10^{-2}$. From radio-astronomical data[75,102] it follows more readily that $\bar{n}_{halo} \gtrsim 10^{-2}$. Actually, the spectrum of the galactic radio radiation has[103] a "kink" at a frequency $\nu_k \simeq 10^7$ cycles. This may be due to the fact that the magnetic-bremsstrahlung losses, at the energy of the electrons that radiate essentially the frequency $\nu_k \simeq 10^7$, are compared with the ionization losses. Hence (see reference 1), $\bar{n}_{halo} \sim 10^3 \nu_k H_\perp \sim 0.03$ when $H_\perp \sim 3 \times 10^{-6}$ oe ($H_\perp$ is the component of the interstellar magnetic field **H** perpendicular to the velocity of the particle). It is hardly possible to reduce this estimate significantly if the interpretation of the "kink" is correct.*

The question of the origin of the relativistic electrons that emit radio waves into the halo is also pertinent to the estimate of the average concentration $\bar{n}$. If these electrons are essentially secondary, i.e., are produced in final analysis as a result of nuclear collisions, then $\bar{n} \sim (1 \text{ to } 3) \times 10^{-2}$ (see Sec. 3e, below, and also reference 104). The secondary electrons would play practically no role at $\bar{n} \sim 10^{-3}$. To be sure, the question of the share of the secondary electrons has not yet been resolved, but there are certain grounds for assuming that it is precisely these electrons that play a dominant role (see Sec. 3e).

Comparing all the arguments given, we can state that at the present time the best founded values are

$$\bar{n} \simeq 10^{-2}\ \text{cm}^{-3}, \quad \bar{\varrho} \simeq 2 \cdot 10^{-26}\ \text{g/cm}^3. \tag{3.1}$$

At this density and at the mean free paths indicated in Table V, we have†

$$\left.\begin{array}{l} T_p = 1.2 \cdot 10^{17} = 3.8 \cdot 10^9\ \text{yr},\ T_\alpha = 9.4 \cdot 10^8\ \text{yr}, T_L = 5.1 \cdot 10^8\ \text{yr}, \\ T_M = 3.6 \cdot 10^8\ \text{yr},\ T_H = 2.5 \cdot 10^8\ \text{yr},\ T_{Fe} = 1.4 \cdot 10^8\ \text{yr}, \end{array}\right\} \tag{3.2}$$

where the subscript "n" is replaced by a subscript indicating the type of nucleus.

The lifetimes of fast nucleons (including nucleons contained in the nucleus) are of the order of the life-

*Unfortunately, the arguments given can hardly be considered convincing, particularly since there is another possible explanation[79] for the "kink."

†We note that if a density $\bar{\rho} = 2 \times 10^{-26}$ and the cross sections given in reference 1 are used, we get $T_p = 3 \times 10^9$ years, $T_M = 3 \times 10^8$ years, $T_H = 1.8 \times 10^8$ years, and $T_{Fe} = 1.2 \times 10^8$ years. The resultant difference is undoubtedly beyond the limits of accuracy of determination of $\bar{\rho}$.

times of the protons. Therefore, the cosmic-ray source power necessary to maintain a quasi-stationary state has an order of magnitude (T is the lifetime and T_p the nuclear lifetime of the protons):

$$U \sim \frac{W}{T} \sim \frac{W}{T_p} \sim 10^{39} - 10^{40} \ \frac{\text{erg}}{\text{sec}} . \qquad (3.3)$$

Here $W = \bar{w}V \sim 10^{56}$ to 10^{57} ergs is the total energy of the cosmic rays in the galaxy, $V \sim (1 \text{ to } 5) \times 10^{68}$ cm^3 is the volume of the entire galaxy and $\bar{w} \sim (0.3 \text{ to } 1)$ ev/cm^3 is the average cosmic-ray energy density (near the earth, $\bar{w} = 0.56$ ev/cm^3; see reference 105). If we assume the present most probable values $V \sim 10^{68}$ and $\bar{w} \sim 0.3$ ev/cm^3, then $W \sim 5 \times 10^{55}$. In addition, the effective nuclear lifetime of the protons for energy losses is 2 or 3 times greater than T_p (see reference 1). Consequently, $U_{min} \sim 10^{38}$ erg/sec. Naturally, the estimate (3.3) remains in force only if $T_e > T_p$, i.e., if the resultant lifetime is $T \simeq T_p$. The uncertainty with which the energy W is known is such that even if a better value is obtained for the effective lifetimes of the particles in the galaxy, the estimate (3.3) could hardly be improved upon at the present time. As will be shown later, other considerations lead to $T_e < T_p$ and $T \sim T_e \lesssim 10^9$ years. In this case $U \sim 10^{39}$ to 10^{41} erg/sec (see Sec. 4d).

We have assumed earlier that the cosmic rays pass freely into the clouds of interstellar gas and that in general the average concentration of the gas in the system, $\bar{n}$, is also the concentration that determines the nuclear lifetime. One can also imagine, however, another situation, where the cosmic rays are essentially located in regions where the concentration is less than average. It was precisely this conclusion that was drawn in reference 106 on the basis of observations of the polarization of the radio emission. The corresponding experimental data are of preliminary character and yield estimates of the concentration of ionized gas only. At the same time, the ionization in the halo may be far from complete,[101] although not small. Furthermore, if the cosmic rays indeed do not penetrate into the regions (clouds) with stronger fields, this is caused by reflection. However, no reflection takes place if the particles move parallel or at sufficiently small angles to the force lines. Therefore, even if the electrons responsible for the radio emission did not penetrate into the clouds, this still would not necessarily mean that the clouds reflect the protons and nuclei capable of moving essentially at smaller angles to the field (see Sec. 3e). In addition, the reflection of cosmic rays that move at large angles to the field by a region with a strong field can be compensated for by the concentration of the force lines (we speak of configurations in which the strong magnetic field does not contain a "frozen-in" flux, i.e., a magnetic flux which is closed inside).

Finally, account must also be taken of the time-averaging element, since the motion of the clouds and the differential galactic rotation will lead, within a period on the order of $T_p \sim 3 \times 10^9$ years, to strong changes in the configuration of the field. Moreover, the configuration of the field probably changes noticeably during one revolution of the galaxy, which in the vicinity of the solar system occurs approximately every 2×10^8 years. As a result, we must assume that allowance for the deviations of the concentration n (which determines the nuclear lifetime) from the value $\bar{n}$ averaged over the entire volume, should not affect all our estimates noticeably.

b) The Role of Cosmic Rays Produced at an Earlier State of Evolution of the Galaxy

Reference 1 employs for the most part a value $\bar{n} \sim 0.1$, corresponding to lifetimes one order of magnitude smaller than (3.2). Therefore, even the longest nuclear lifetime for protons, $T_p \sim 4 \times 10^8$ years, is assumed small compared with the age of the galaxy, which is now believed to be $T_G \sim (8 \text{ to } 10) \times 10^9$ years. Reducing the concentration $\bar{n}$ by one order of magnitude changes somewhat the situation and makes the lifetimes T_p and T_G commensurate. In this connection, naturally, a discussion arises concerning the role of the cosmic rays produced at the earliest stage of the evolution of the galaxy (see reference 4, p. 421, and reference 107). A decisive argument (see, in particular, reference 102) against the assumption that the cosmic rays observed by us were produced at earlier stages (approximately 8×10^9 years ago) is that the inequality $T_{Fe} \ll T_G$ is retained when $\bar{n} \gtrsim 3 \times 10^{-3}$. Actually, even when $\bar{n} \simeq 10^{-3}$ we have $T_{Fe} \simeq 1.4 \times 10^9$ years and $T_{Fe}/T_G \simeq 6$, that is, the flux of iron would be reduced by approximately 300 times in 8×10^9 years. On the other hand, if $\bar{n} = 10^{-2}$, then the flux of the iron nuclei would now decrease by a factor 10^{25}! Thus, only protons could have been formed at the earlier stages. At the same time, there are no grounds whatever for doubting the common origin of the protons and the nuclei; moreover, most protons are secondary (see Sec. 4d). Furthermore, the total lifetime T is obviously shorter than the nuclear lifetime and, as will be shown below, the estimated time of escape of the particles from the galaxy is $T_e < 10^{10}$. Therefore, even when $\bar{n} \sim 10^{-3}$ there is still no certainty of the need for accounting for cosmic rays of earlier origin. It must also be kept in mind that the density of the gas in the galaxy was probably higher in the past than now. It follows therefore, that at the present-day concentration $\bar{n} \sim 10^{-3}$, a larger value would have to be assumed for the average concentration over a period of $10^9 - 10^{10}$ years.[104]

Summarizing, we see no reasons for assuming the cosmic rays produced at an earlier stage of the evolution of the galaxy to be of importance. This point of view can be considered only within the framework of a model (which meets with serious objections) in which the average concentration of the gas is $\bar{n} < 10^{-3}$ cm^{-3}, and the time of escape of the cosmic rays from the system is $T_e > (3 \text{ to } 8) \times 10^9$ years.

c) Character of Motion and Escape of Cosmic Rays from the Galaxy

Let us stop to discuss the character of motion of the cosmic rays in galactic magnetic field. To explain this point we must first obtain sufficiently complete data on the configurations and the intensities of the magnetic fields themselves. Actually, we know very little on this subject. Certain data concerning the field in the spiral were already discussed in Sec. 2b, where arguments in favor of the assumption of a sufficiently free exchange of cosmic rays between the spiral and the halo were presented.* There is no direct information on the structure of the field outside the spiral, and particularly in a halo, if we disregard certain indications, mentioned in Sec. 2b, in connection with the question of the nature of the "radio belt." At the same time, there are many considerations in favor of the assumption of a random (essentially) character for the field in the halo. Thus, the radio emission from the halo is sufficiently uniformly distributed in all directions, as would be expected for a random field as a result of averaging. Furthermore, the halo rotates much more slowly than the spiral (otherwise the halo would not be quasi-spherical). On the other hand, if an ordered field exists in the halo, connected in some manner with the ordered field in the spiral, one would expect a simultaneous rotation of the halo and the spiral. The random character of the field in the halo is also assumed[101] in the best-founded dynamic theory of the halo.†

It is natural to use the diffusion approximation for a random field, as is done in reference 1. This means that the motion of the cosmic rays is compared to the diffusion of molecules in a gas at a velocity v, equal to the velocity of motion along the force lines ($v \sim c$) and an effective mean free path l, which characterizes the configuration of the field (in the simplest case l is the dimension of the region with the quasi-homogeneous magnetic field). One of the possible objections to such a diffusion model is that the cosmic rays should be so to speak "glued" to the force lines and therefore cannot diffuse in all directions. It must be taken into account, however, that there exists a particle drift due to the inhomogeneity of the field, which causes some cosmic rays to move from some flux lines to others. The drift velocity in a direction perpendicular to the field H and to the direction of the gradient ∇H has an order of magnitude

$$v_d \sim \frac{r}{L} v_\perp, \quad r = \frac{E \sin\theta}{300ZH}, \quad v_\perp = c \sin\theta, \tag{3.4}$$

where L is the characteristic dimension of the inhomogeneity of the field, r is the radius of curvature, and θ is the angle between the velocity of the particle and the direction of the field (we assume, for simplicity, that the velocity is equal to that of light, c, an assumption which is incorrect only for the softest cosmic rays). When $E \sim 10^{10}$ ev, $H \sim 3 \times 10^{-6}$ oe, $\sin\theta \sim 1$, and $Z \sim 1$, we have $r \sim 10^{13}$ cm and $v_d \sim 10^3$ cm/sec at $v_\perp \sim 10^{10}$ and $L \sim l \sim 30$ parsec $\simeq 10^{20}$ cm. During a lifetime $T \sim 10^{17}$ sec the particles will drift in this case approximately 30 parsec. Such a displacement, although small, can still lead to a considerable mixing of the cosmic rays.* The situation is analogous here to that obtained when the position of some molecule in a gas is displaced slightly. This displacement will change radically the subsequent fate of this particular molecule, which may find itself in the opposite side of the vessel, compared with a molecule which was not subject to displacement. By virtue of this, the diffusion approximation in the case of the halo can nevertheless be approximately applicable (naturally, assuming that the field in the halo is random or only weakly ordered). Furthermore, we must not forget that the parameter l, or better still the coefficient of diffusion $D = lv/3$, has the meaning of a certain effective value and is free within certain limits (it should be determined from a comparison of the calculation with the observational data). Therefore, for "open" arms (that is, in the case when the foregoing assumption of the free exchange of cosmic rays between the arms and the halo is correct) the role of the arms in the overall balance of the cosmic rays in the galaxy should be small. Individual regions inside the arm (in particular, the region of the solar system) differ little in this picture from any other region in a quasi-homogeneous field. Naturally, within the confines of such regions, the dimensions of which are on the order of the mean free path, one does not have to speak of diffusion, and the motion of the cosmic rays is ordered. At the same time, naturally, the distribution of the directions of the cosmic rays can be completely isotropic even in a homogeneous field, as takes place near the earth. This fact cannot be related, at least for particles with high energy, with the influence of interplanetary mag-

*We note that even if the length of the spiral is 100 kiloparsec $= 3 \times 10^{23}$ cm and an ordered field exists, a relativistic particle moving along the force lines with a velocity $v \sim 10^{10}$ would pass through the spiral in merely some 3×10^{13} sec $= 10^6$ years.

†See also Note Added in Proof, III.

*In estimating the role of the drift, from the point of view of its effectiveness as a stirring mechanism, we disagree somewhat with Davis.[109] Undoubtedly, the foregoing arguments are not the only ones that apply to this question and a detailed investigation is necessary. We note also that many data are evidence in favor of values $l < 30$ parsec and a value $l \sim 3$ to 10 parsec cannot be excluded (see Sec. 4d). When $L \sim l \sim 3$ parsec the path covered as a result of the drift within a time T_p is now on order of 300 parsec.

netic fields* and it serves as still another argument in favor of the assumed model. Actually, were the cosmic rays and the arms noticeably isolated from the cosmic rays in the halo, and were the field in the arms homogeneous, a noticeable anisotropy in the directions of the cosmic rays would be expected. This anisotropy, for example, could be due to the fact that the particles moving at small angles to the field would escape the system more rapidly and thus leave in the arms, for the most part, particles that rotate in a circle or along a helix of small pitch.

All the foregoing considerations, naturally, still do not prove the correctness of the diffusion model and of the entire picture in general. But they do prove, in our opinion, not only that such a model is possible but also that it is probable to some extent. Furthermore, it is quite difficult to imagine that the diffusion approach to an analysis of the cosmic rays in the galaxy (as a whole) could lead to major errors of qualitative character or would be unsuitable for estimates.† Another point is that in quantitative calculations, encountered when determining the chemical composition of cosmic rays, the diffusion approximation may no longer be sufficient. We shall return to this question in Sec. 4d. Here, however, we shall use the diffusion model to estimate the time of escape of the particles from the galaxy, T_e. Within the framework of this model, the cosmic rays, which are produced predominantly near the galactic plane and the galactic center, diffuse toward the boundaries of the halo. Neglecting reflection, the total flux at a distance R from the center is in this case of the order $S_0 \sim D\frac{dN}{dr}4\pi R^2 \sim 4vlNR$, since $D = lv/3$ and $dN/dr \sim N/R$ (N is the concentration of the cosmic rays). Assuming $R \sim 5 \times 10^{22}$, a velocity of motion along the field $v \sim 10^{10}$, $l \sim 3 \times 10^{19}$ to 3×10^{20}, and $N \sim 10^{-10}$, we obtain $S_0 \sim 10^{43}$ to 10^{44} sec^{-1}. Evidence in favor of the value $l \sim 10$ parsec $= 3 \times 10^{19}$ cm ($D \sim 10^{29}$ cm^2/sec) are certain calculations, which make use of regular astronomical data,[60] whereas information on clouds in the halo and other considerations lead to estimates $l \sim 100$ parsec and $l \sim 75$ parsec respectively.[96] Thus, in spite of the approximate nature of the estimate, there are grounds for assuming that the flux is $S_0 > 10^{42}$. At the same time, the total number of cosmic rays in the galaxy is $NV \sim 10^{58}$ to 10^{59}, which means that an injection of $NV/T_p \sim (10^{58}$ to $10^{59})/10^{17} \sim 10^{41}$ to 10^{42} particles per second is necessary to make up for the nuclear losses. Thus, if reflection from the galactic boundaries is neglected, we would apparently have the inequality $T_e < T_p$. From energy considerations, therefore, it would be desirable to limit the escape of cosmic rays into metagalactic space. A stronger reflection would take place in the case of a "closed model" in which the galaxy represents a "cage" of force lines, and not a system with an "open" magnetic field. According to certain estimates (see below), the field in intergalactic space is $H_{IG} \sim 10^{-7}$ to 10^{-8}; the field in the halo is $H \sim 3 \times 10^{-6}$ to 10^{-5}. Therefore, in the closed model, only approximately 1% of the flux lines leave the halo, corresponding (in first approximation) to an escape of 1% of the cosmic rays that reach the boundary. As a result, a total of $S \sim 10^{-2} S_0 \sim 10^{41}$ to 10^{42} particles/sec escape the halo, and this is fully compatible with the estimate $T \simeq T_p$ for the total lifetime. We note that in a field $\sim 10^{-5}$ oe the radius of curvature is $r \sim 10$ parsec $\lesssim l$ at an energy $\epsilon \sim 10^{17}$ ev/nucleon, and consequently, at least if drift is disregarded, the very heavy particles will escape the halo much more slowly than they will be lost by collision even when $E \sim 10^{19}$ ev.

Thus, if the particles with energy $E \lesssim 10^{19}$ are heavy nuclei, the assumption that they are of galactic origin does not raise any difficulties, at least as regards the "transparency" of the galaxy for particles with sufficiently high energy.

This conclusion remains in force, apparently, if escape from the system due to drift in an inhomogeneous magnetic field is taken into account.[102,110] The rate of the drift is determined by Eq. (3.4). The escape of particles due to drift can be estimated at

$$S_d \sim v_d N' 4\pi R^2 \xi \sim \frac{10^2 \varepsilon R^2 N' \xi \sin^2\theta}{HL}. \quad (3.5)$$

Here N′ is the concentration of the particles considered and ϵ is the energy (ev/nucleon); the factor $\xi \le 1$ takes into account the fact that the drift is perpendicular to the field and to its gradient, and consequently, it may not cause particles to leave the system. Nuclear collisions cause $S_n \sim 4\pi R^3 N'/3T_n$ particles/sec to disappear from the system, and consequently

$$\beta = \frac{S_d}{S_n} \sim 3 \cdot 10^8 \frac{\varepsilon T_n \xi \sin^2\theta}{HRL}. \quad (3.6)$$

The maximum possible value of β is reached, in practice, when $\xi \sim 1$, $\sin^2\theta \sim 1$, $H \sim 3 \times 10^{-6}$ and $L \sim l \sim 10^{20}$, with $\beta_{max} \sim 10^{-29} \epsilon T_n$. For heavy nuclei, $\beta_{max} \sim 1$ at $\epsilon \sim 10^{13}$ to 10^{14} ev/nucleon. Actually, however, in all probability $\xi \ll 1$ (in an axial field, for example in a dipole field, $\xi = 0$; the value of ξ can be exceedingly small also in more complicated fields, as is evidenced by the stellarator). No less important is the fact that the characteristic dimension of the field L in (3.5) and (3.6) pertains to the field of the halo as a whole, and thus, it is more likely that $L \lesssim R \sim 5 \times 10^{22}$. Putting $L \sim 10^{22}$, $\xi \sim 3 \times 10^{-2}$, and $\sin^2\theta \sim 1/3$, we obtain $\beta \sim 10^{-33} \epsilon T_n$ and, for heavy nuclei, $\beta \sim 1$ at ϵ

*The radius of the solar system is approximately 10^{15} cm and there are no grounds for assuming the existence beyond these boundaries of magnetic fields of solar origin having an intensity greater than 10^{-6} or 10^{-5} oe. At the same time, the cosmic rays with high degree of isotropy are those of energy greater than, say, 3×10^{13} ev, for which the radius of curvature in a field of $H \sim 10^{-5}$ oe is greater than 10^{16} cm.

†We do not mean here, naturally, the relatively small regions (in time intervals), in which magnetic traps can be formed.

$\sim 10^{17}$ to 10^{18} ev/nucleon, while for protons $\beta \sim 1$ at $E \sim 10^{16}$ ev. Thus, the yield due to drift can be significant (for the assumed values of L and ξ) only for protons with $E > 10^{16}$ ev.

The previous discussion pertained to the "closed model" of the galaxy, in which the reflection of the cosmic rays from the galactic boundaries takes place with a coefficient close to unity. However, such a model cannot yet be considered confirmed by observational data. In the second hypothetical case, for the "open model," the field diminishes smoothly toward its metagalactic value, and the cosmic rays diffuse freely into metagalactic space. Here, as follows from the given estimates, $T_e < T_p$ or even $T_e \ll T_p \sim 3 \times 10^9$ years. In the latter case, the lifetime of the cosmic rays is $T \simeq T_e \ll 3 \times 10^9$ years, and for example, $T \sim 3 \times 10^8$ years. In this version, compared with the closed model, the number of injected cosmic rays should be one order of magnitude greater. From the energy point of view, this is still permissible (see Sec. 4a). The third possible model is that of an unstable halo with reflecting walls. Unlike in the "closed model," the halo is not stable in this case,[101] and if a sufficiently large number of cosmic rays accumulate, they erupt from the system in some direction, and carry with them both the gas and the magnetic field. Such a model, from the point of view of the balance of the number and of the energy of the cosmic rays, is apparently close to the "open model." One might think that further radio-astronomical investigations with instruments of high angular resolving power will also lead to certain progress as regards the character of the transition (boundaries) between the galaxies and the metagalactic space. It is interesting that the coefficient of reflection from galactic boundaries greatly influence the chemical composition of the cosmic rays. Furthermore (and this is somewhat unexpected), within the framework of the diffusion approximation the observed chemical composition of the cosmic rays is, in general, incompatible with the "closed model" (see Sec. 4d). Thus, the escape of cosmic rays from the galaxy is possibly quite substantial. Postponing further discussion of this question to Secs. 4c and 4d, we shall estimate in what follows, for the sake of simplicity, the source power for the "closed model." As already mentioned, the use of the "open model" will increase the power by probably only one order of magnitude, for if the diffusion picture is correct, then the cosmic rays will leave the system relatively slowly even in the absence of reflection from the galactic boundaries [for example, $T \sim (3 \text{ to } 10) \times 10^8$ years instead of $T \sim 3 \times 10^9$ years for the "closed model"].

The estimated role of the drift is essentially independent of the model. We must merely replace, in the case of the open model, the time T_n in (3.6) by T, where $1/T = 1/T_e + 1/T_n$. For protons, $T_n \equiv T_p \sim 3 \times 10^9$, and when $T_e \simeq T \sim 3 \times 10$, the coefficient β [see (3.6)] is decreased by one order of magnitude. For heavy nuclei, on the other hand, the foregoing estimate of β remains in force in this case, too.

d) Cosmic Rays of Metagalactic Origin

Were there really a rather rapid escape of high-energy cosmic rays from the galaxy at energies $E > E_k \ll 10^9$ ev (the energy E_k corresponds to a value $\beta = 1$), then the cosmic rays in the region $E > E_k$ would have to be assumed to be essentially of metagalactic origin. With this, a "kink" would be expected in the energy spectrum of the cosmic rays at $E \sim E_k$. The question of the existence of such a "kink" is still moot; furthermore, it might be smeared and, on the other hand, due not to the appearance of metagalactic cosmic rays, but to a change in the chemical composition of the galactic cosmic rays (see Sec. 1b). Thus, the situation remains unclear in this respect. In any case, however, in the model assumed, cosmic rays of metagalactic origin either play no noticeable role at all, or are responsible only for the particles with $E \gtrsim E_k$.

If we disregard the cosmic-ray origin theories[4,111] that are based on the premises of the steady state cosmology,* the cosmic rays should enter the metagalactic space from the galaxies. On the average there is one galaxy in a volume of 3×10^{73} to 10^{75} cm^3 (the density of the galaxies is very uneven), our own galaxy being of average size. Let us assume as a very rough estimate that the flux of cosmic rays from the galaxies is on the average not more than $10^{42} - 10^{43}$ particles per second per galaxy, as from our own galaxy. After approximately 10^{10} years, such a flux will lead to a cosmic-ray density in the metagalaxy $N_{MG} \lesssim 10^{-13}$ to 10^{-14} particles/cm^3 and to an average energy density $\overline{w} \lesssim 10^{-3}$ to 10^{-4} ev/cm^3. Thus, using the equality $\overline{w} = H_{MG}^2/8\pi$, we obtain a field $H_{MG} \lesssim (5 \text{ to } 20) \times 10^{-8}$ (an independent estimate[98] leads to a value $H_{MG} \sim 10^{-7}$; at the same time, the concentration assumed in reference 98 for the cosmic rays is unreasonably large, since the energy density of the cosmic rays

*The fate of such cosmological theories must surely not be determined primarily from astrophysical considerations and data which have no relation to the problem of the origin of cosmic rays. In addition, the corresponding theories of the origin of cosmic rays have not been sufficiently developed, and the more specific of these theories[111] is subject to a number of difficulties, which have been analyzed by V. A. Razin. Thus, it is assumed in reference 111 that the energy density of the cosmic rays in the metagalaxy is $\overline{w} \sim 1$ ev/cm^3, and hence the equilibrium magnetic field is $H \sim \sqrt{8\pi\overline{w}} \sim 5 \times 10^{-6}$ oe. The existence of such a field contradicts the radio-astronomical data, and at the same time it is more likely that $H^2/8\pi > \overline{w}$ rather than vice versa. Furthermore, reference 111 does not allow for the fact that in the expansion of this system, the formula customarily used for the change of energy in statistical acceleration is incorrect and it is necessary to take into account the slowing down of the particles due to the expansion [see reference 112 and (3.8) below].

will be approximately two orders of magnitude greater than the energy density of the field).

Let us note that the penetration of the cosmic rays into the galaxy is greatly hindered under the conditions when the metagalactic field is considerably weaker than the galactic field. In a galactic model with a "boundary" this is directly clear from the statement made in Sec. 3b. But this statement remains in force also in the absence of a "boundary," when the particles that move at angles θ (with the field) which are not too small will be reflected from the region with the stronger field, owing to the conservation of the adiabatic invariant [see Eq. (3.11)].

In connection with the discussion of the possible role of cosmic rays of metagalactic origin, we must emphasize the following important point: within the framework of the evolutional cosmology, even without account of the effect of the recession of the galaxies, cosmic rays can reach us only from a very limited region of the metagalaxy. Actually, during the time of existence of the galaxies, $T_{MG} \sim T_G \sim 10^{10}$ years, assuming the motion of the cosmic rays to be diffuse, they will traverse a distance

$$R_{\max} \sim \sqrt{2DT_{MG}} = \sqrt{\tfrac{2}{3}\, lvT_{MG}} \sim 5\cdot 10^{13}\sqrt{l}\ \text{cm} \qquad (3.7)$$

(the speed of the cosmic rays along the field is $v \sim 10^{10}$ cm/sec). Even in a metagalactic field $H_{MG} \sim 10^{-8}$ (at $Z = 1$, $\sin\theta \sim 1/3$, and $E \sim 10^{18}$ ev), the radius of the curvature is $r = E \sin\theta/300H \sim 10^5 E \sim 10^{23}$ cm. At the same time, the average distance between the galaxies is $(3 \text{ to } 10) \times 10^{24}$ cm and the characteristic scale of the quasi-homogeneity of the metagalactic field is probably not more than 10^{25} cm. Therefore the use of (3.7) is justified, and $R_{max} \sim (5 \text{ to } 15) \times 10^{25}$ cm $\simeq (2 \text{ to } 5) \times 10^7$ parsec (at $l \sim 10^{24}$ to 10^{25}). Account of the time variation of the distance between the galaxies will not change this rough estimate substantially, since both the distance R and the mean free path l are smaller at the earlier stages. Furthermore, allowance for the "recession" of the galaxies, which leads to the well known red shift of the spectral lines, does in itself imply a limited distance from which the cosmic rays can arrive in the galaxy. This conclusion is simply connected with the fact that the particle flux is sharply decreased as the particle source moves away at a velocity greater than the diffusion velocity. To estimate this we neglect, as in reference 113, the variation of the effective mean free path with time, that is, we put $R = \sqrt{2Dt} = \sqrt{2lvT/3}$, from which we get a diffusion velocity $(dR/dt)_D = lv/3R$. At the same time, the distance to the galaxies varies, due to the recession, as $(dR/dt)_{MG} = HR$, $H \sim 1/T_{MG}$, where H is the Hubble constant. From the condition $(dR/dt)_D \sim (dR/dt)_{MG}$ we arrive at an estimate of the maximum radius $R_{max} \sim \sqrt{lvT_{MG}/3}$; this estimate agrees with (3.7), for the small difference in the numerical factor is beyond the accuracy of the calculation. Thus, the cosmic rays can reach the galaxy apparently only from distances less than approximately $(2 \text{ to } 5) \times 10^7$ parsec, which is smaller, by a factor of several times ten, than the radius of the part of the metagalaxy observable in the strongest telescope.

A volume with a radius $R \lesssim R_{max} \sim 10^{26}$ cm contains $\sim 10^4$ galaxies, which have been much more thoroughly investigated than the more remote systems. The radio source A Cygni is $\gtrsim 10^8$ parsec $> R_{max}$ away. The distance to the three powerful sources A Virginis, A Centauri, and A Fornacis (see Table IV) is less than R_{max}, but apparently there are no other sources of comparable energy in this region.* Even considering that the energy of the cosmic rays in each of these sources is one thousand times higher than the energy of the cosmic rays in the galaxy, we conclude that they play a relatively small role from the point of view of determining the density of metagalactic cosmic rays. In other words, the foregoing estimate of the cosmic-ray energy density outside the galaxy does not change if the powerful sources are taken into consideration.

More important is another point: the relatively low value of R_{max} and the small number of powerful objects raises doubts concerning the possibility of obtaining any considerable flux of cosmic rays with energies essentially greater than those which can still be obtained in normal galaxies, for example, as a result of flares of supernovae. To this we must add that statistical acceleration in metagalactic space is ineffective in the evolutional cosmological model. Actually, in the statistical mechanism of acceleration of relativistic particles we have

$$\frac{dE}{dt} = (\alpha_1 + \alpha_2) E, \quad \alpha_1 \sim \frac{u^2 v}{c^2 l}, \quad \alpha_2 \sim -\frac{Vv^2}{Rc^2}, \qquad (3.8)$$

where u is the velocity of random motion, v the velocity of motion along the field, and V/R the ratio of the velocity of the expansion of the shell to its radius (see reference 112 and 1); in the case of the metagalaxy we have

$$\frac{V}{R} \simeq H \sim \frac{1}{T_{MG}} \sim 3\cdot 10^{-18}\ \text{sec}^{-1}.$$

When $u \sim 3 \times 10^7$, $v \sim c$, and $l \sim 3 \times 10^{24}$ we get $\alpha_1 \sim 10^{-20} < |\alpha_2|$ and $\alpha_1 + \alpha_2 < 0$, i.e., a general slowing down rather than acceleration (naturally, within the time $t < T_{MG}$ the effect of this slowing down is insignificant; the smallness of α_1 was noted earlier in reference 114). We can therefore speak of acceleration only when referring to clusters of galaxies.[115] Neglecting for clusters the term $\alpha_2 E$ (this is apparently legitimate, for otherwise the acceleration would be

*To this we must add that the characteristic "spike" which indicates the existence of particularly strong fields and high-energy electrons, is observed only for A Virginis and is missing even from the other two powerful sources.

even smaller or would be replaced by deceleration) *we obtain for the local group of galaxies, including* our own, $\alpha_1 \lesssim 10^{-20}$ to 10^{-21} (for $u \sim 10^7$ and $l \sim 10^{24}$). For the cluster of galaxies in Coma, values $u \sim 2 \times 10^8$ and $l \sim 3 \times 10^{22}$ are assumed in reference 115, and consequently $\alpha_1 \sim 4 \times 10^{-17}$. This means that within a time on the order of T_{MG} the energy of the particles increases by a factor $\exp(\alpha T_{MG}) \sim 10^5$. Actually, however, the assumed value of l appears to be too low, and one should use at least $l \sim 10^{23}$, $v \sim 10^{10}$, and $\alpha_1 \sim 4 \times 10^{-18}$, $\exp(\alpha T_{MG}) \sim 1$. On the other hand, the cluster in Coma is approximately 7×10^7 parsec $> R_{max} \sim (2 \text{ to } 5) \times 10^7$ parsec away, and is exceptional in its characteristics (at least, *there are no nearer clusters that are comparable in* the sense of possible efficiency of acceleration[115]). We can conclude therefore that even clusters of galaxies located $R \lesssim R_{max}$ away are also unable to accelerate the cosmic rays noticeably. Thus, only a few exceptional sources (primarily A Virginis) are capable of making a contribution to the metagalactic cosmic rays in the region of our galaxy, qualitatively *different from the contribution of the normal galaxies.* But this again leads to the conclusion that the metagalactic cosmic rays play an insignificant role in the galaxy.

As regards particles with energy $\epsilon > 10^{17}$ ev/nucleon ($E > 10^{18} - 10^{19}$ ev for nuclei), which are actually very difficult to accelerate in the galaxy (see Sec. 4b), the following must be noted. First, it is not known whether such particles exist (their existence would be proved were the observed particles with $E \sim 10^{18} - 10^{19}$ identified with certainty as protons). Second, it is very difficult to imagine that metagalactic particles with $\epsilon > 10^{17}$ ev/nucleon, which are formed only in excep*tional sources, can exist precisely in the same amount* corresponding to the extrapolation of the spectrum of galactic cosmic rays (in other words, the appearance of a noticeable metagalactic component should, probably, be accompanied of necessity by a "kink" in the spectrum). Third, even if the metagalactic component and the strongest known sources are taken into account, a practical cutoff of the spectrum of cosmic rays at $E \sim 10^{19} - 10^{21}$ ev is fully possible.

To be sure, we ignored earlier the possibility that the cosmic rays had been produced in metagalactic space at an earlier stage, when the galaxies were formed, or somewhat earlier. Since the concentration *of the gas between the galaxies is now* $\bar{n} \lesssim 10^{-4}$, even the heavy nuclei contained in the metagalactic cosmic rays do not have time to decay within $T_{MG} \sim 10^{10}$ years. However, were the density of the cosmic rays between galaxies to be greater ($\bar{w} \sim 1$ ev/cm^3), the appearance of a relatively strong magnetic field would be expected there, and this would lead, generally speaking, to an impossibly high intensity of metagalac*tic radio emission.* In addition, a colossal energy would be concentrated in metagalactic space in this case. But, if the average energy density in the meta*galactic cosmic rays produced at the earlier stage* were sufficiently small, their contribution would not change the picture referred to above (it would be difficult, however, to draw in this case any definite conclusions concerning the maximum energy of the cosmic rays). On the other hand, we know of no convincing arguments that enable us to conclude a high acceleration efficiency (with allowance for the time factor) at the earlier stages. Thus, this point can be clarified only if the existing cosmological representations are substantially refined.[116]

It is necessary to bear in mind at the same time that, according to modern ideas, the nuclei (particu*larly the heavy ones) are produced in stars (see, for* example, references 116a and 141). It follows therefore, that the bulk of the cosmic rays in the galaxy, connected with the acceleration of the nuclei (see Secs. 1a and 4d), can all the same not result from acceleration of the particles within the period preceding the formation of the galaxies and the stars.

e) Origin of Electronic Component of Cosmic Rays

The relativistic electrons, which make up the electronic component of the cosmic rays in the galaxy, can enter the interstellar space from the primary cosmic-ray sources (primarily, from the shells of supernovae), or can be formed directly in the interstellar medium. In the latter case (of secondary origin) the electrons are produced as a result of π-μ-e decay of pions produced in nuclear collisions between cosmic rays and the nuclei of interstellar gas.* We assume that 5% of the energy of the primary nucleon[105] goes into electrons (and positrons) (in reference 1 a value 2.5 to 7.5% is assumed for a single collision and 5 to 15% of the total *energy of the protons leaving the cosmic rays).* Then the total energy going into the electrons in the galaxy is [see (3.3)]:

$$U_e \sim 5 \cdot 10^{-2} U \sim 5 \cdot 10^{-2} (10^{39} - 10^{40}) \sim 5 (10^{37} - 10^{38}) \frac{\text{erg}}{\text{sec}}. \tag{3.9}$$

At the same time, it follows from radio-astronomical data that the electrons lose in the galaxy 10^{38} to 10^{39} erg/sec to radio emission [see reference 1, formula (3.43) with $V \sim 10^{68}$ to 10^{69}]; another more direct estimate (reference 4, p. 421) of the electron loss is $\sim 3 \times 10^{38}$ erg/sec. Thus, the radio emitting electrons can actually be secondary, but apparently only if the assumed average concentration of the gas along the path of the cosmic rays is $\bar{n} \sim 10^{-2}$ or even $\bar{n} > 10^{-2}$. With $\bar{n} \sim 10^{-3}$ there would be at least 5 — 10 times fewer electrons than are needed to explain the overall

*The electrons produced in the β decay of neutrons and unstable nuclei have velocities which are approximately equal to the velocities of these neutrons and nuclei. Consequently the β-electron energy for the main part of the cosmic rays is $E \ll 10^8$ ev, i.e., it is outside of the energy interval $E \gtrsim 10^8$ ev which is of interest to us in the case of the general galactic radio emission.

galactic radio emission. To the contrary, if it could be proved from independent considerations that $\bar{n} \simeq 10^{-2}$, then this would be a strong argument in favor of the secondary origin of the electrons (to be sure, such an argument could not be decisive, in view of the inaccuracy in the estimate of the power U_e: as is clear from (3.9), even when $\bar{n} = 10^{-2}$ the value of U_e can still be about one-sixth the radiated power, which is equal to $\sim 3 \times 10^{38}$ erg/sec).

If we consider the energy balance only, the energy of the radiating electrons can also be replenished from primary sources. Thus, estimates given in reference 1 show that supernovae alone ensure the appearance of relativistic electrons with an average power of 10^{36} — 10^{39} erg/sec. The important question arises of the choice between the two available alternatives, since it is little likely that the primary and secondary particles play approximately equal roles (such a possibility is, naturally, not excluded in principle).

The origin of the electrons, if we disregard possible refinements of the values of the power and of the gas concentration $\bar{n}$ given above, can be determined in three ways. First, the primary component should consist of approximately equal amounts of electrons and positrons. At the same time, only electrons can escape from the shells of the supernovae; this will take place if the electrons are not formed in the shells by nuclear collisions. Consequently, if the primary electronic component of cosmic rays on earth were to contain only electrons (i.e., no positrons), this would serve as decisive evidence against assuming them to be of secondary origin. Unfortunately, no electrons have been observed at all in the primary cosmic rays ($E > 10^9$ ev), although a measurement of their flux is very important from the point of view of a possible refinement of the estimates that radio-astronomical data provide for this flux (see reference 1). The use of artificial earth satellites and of space rockets obviously uncovers new possibilities of measuring the flux of electrons near the earth and in the solar system.

Secondly, one can seek for a clue to the origin of galactic radiating electrons by investigating the conditions of escape of electrons from the sources and the character of their motion in interstellar magnetic fields. We know that when a particle moves in a field that varies sufficiently slowly in time and in space, the adiabatic invariant is conserved:

$$\frac{p_\perp^2}{H} = \frac{p^2 \sin^2\theta}{H} = \text{const}, \qquad (3.10)$$

where $p_\perp$ is the component of the particle momentum **p** perpendicular to **H**, and θ is the angle between **p** and **H**.

If the time variation of the field can be neglected, then $p = \text{const}$ and (3.10) becomes

$$\frac{\sin^2\theta}{H} = \text{const}. \qquad (3.11)$$

The change in the energy of the particles that wander in the galaxy, according to estimates given in reference 1, is quite small.* The same can apparently be said concerning the energy change that accompanies escape from the shells of supernovae, at least during the period that precedes their strong expansion and spreading. Assuming therefore the conservation law (3.11), we see that the angle θ is decreased on going from a region with a strong field into a region with a weak field. This is precisely the situation when the particles leave the shells, where $H \sim 10^{-3}$ to 10^{-4} oe, and go to the interstellar space where $H \sim 3 \times 10^{-6}$ to 10^{-5} oe. Therefore, even if $\sin^2\theta \sim 1$ in the shells, we have $\sin^2\theta \sim 10^{-1}$ to 10^{-2} for the escaping particles. The radio-emitting ability depends in turn on $\sin\theta$ and, specifically,

$$I_\nu = \text{const}\, H_\perp^{\frac{\gamma+1}{2}} = \text{const}\, H^{\frac{\gamma+1}{2}} (\sin\theta)^{\frac{\gamma+1}{2}}$$

[see (2.1) and reference 1]. When $\gamma = 2.4$ and the invariant (3.11) is conserved, this means that the intensity of radiation is proportional to $(\sin\theta)^{3(\gamma+1)/2} = (\sin\theta)^{5.1}$ or, for a specified field H, it is proportional to $(\sin\theta)^{(\gamma+1)/2} = \sin(\theta)^{1.7}$. It follows therefore[120] that when the adiabatic invariant is conserved in interstellar space and the radiating electrons are of primary nature, their number should be one or two orders of magnitude greater than that assumed in reference 1. But the estimate given in reference 1 for the concentration of electrons with energies greater than 10^9 ev is $N_e\ (E > 10^9) \sim 5 \times 10^{-13}\ \text{cm}^{-3}$ for $H_\perp \sim H \sim 10^{-5}$ to 5×10^{-6}. If, however, $H_\perp = H \sin\theta \sim 10^{-6}$ to 3×10^{-7}, then $N_e\ (E > 10^9) \sim 3 \times 10^{-12}$ to 3×10^{-11}, whereas near the earth $N_e\ (E > 10^9) < 10^{-12}$ (the situation is analogous in the estimate of N_e for the disk, see reference 91 and Sec. 2b). From energy considerations, a significant increase in the concentration of the electron component of the cosmic rays is also undesirable. Thus, if the adiabatic invariant (3.11) is conserved, the assumption that the galactic electrons are primary certainly gives rise to difficulties. Unfortunately, it is precisely the question of the conservation of the invariant (3.11) as the cosmic rays wander in the galaxy which needs clarification. Inasmuch as the radius of curvature $r = E \sin\theta / 300\, H$ is quite small for the bulk of the cosmic rays (for example, even when $E \sim 10^{10}$, $\sin\theta \sim 1$, and $H \sim 3 \times 10^{-6}$, we get $r \sim 10^{13}$ cm), a change in the adiabatic invariant is possible only if the cosmic rays cross the

*If the strong attenuation of magnetohydrodynamic waves in interstellar medium[117-119] is taken into account, we become even more convinced that effective statistical acceleration of the particles can take place only in regions such as the shells of supernovae or in stellar atmospheres.

fronts of the magnetohydrodynamic shock waves.* The width of such fronts is apparently on the order of the radius of the curvature of the trajectories of the protons in the interstellar medium, i.e., it is considerably less than the radius of curvature of the cosmic rays. However, it is still insufficiently clear how the angle θ will change when a fast particle passes through the fronts of magnetohydrodynamic waves of different types. Furthermore, it is unclear how many and which fronts will be encountered by the cosmic-ray particles. Consequently, only after these questions are clarified can we evaluate the role of magnetohydrodynamic waves as a mechanism that "stirs up" the cosmic rays over the angle θ. If the efficiency of this mechanism is low, we must take into consideration the fact that the primary particles (protons, nuclei, and electrons emitted by the sources) move at angles $\theta \ll 1$. When $\theta \ll 1$, the penetration of the particles into the regions with stronger fields becomes easier, and the drift velocity (3.4) decreases. Undoubtedly more exact information on the character of motion of the cosmic rays in galactic magnetic fields (see Sec. 3c) must be obtained, with account of the remarks made concerning the role of (3.11).

The third possibility of explaining the origin of galactic electrons is connected with the use of radio-astronomic data.[67,96,102] The secondary electrons are formed both in the "disk" and in the halo, and their energy spectrum, meaning also the radio spectrum, should therefore be approximately the same in the halo and in the "disk." On the other hand, the primary electrons enter the halo from the spiral and from the central regions of the galaxy, and lose energy on the way. As a result, in the latter case one might expect a certain change in the spectrum of the radio emission on going from the center of the galaxy to its periphery. As far as we know, there are no such changes, but neither the accuracy of measurement nor the character of the calculations can lead at the present to far reaching conclusions.*

The same can be said with respect to attempts to deduce that the interstellar electrons are of secondary origin, on the basis of the similarity between the spectra of the general galactic radiation and the radiation of most discrete sources (reference 4, p. 421). If the electrons in the shells of the supernovae and in the interstellar space were formed during the first stages of the explosion, but some were "snared" in the shell while others did escape from it, then the spectra are indeed expected to be similar. To the contrary, if the electrons emerge from the shell only after the latter diffuses, with a spectrum $N_{e0}(E) = K_0 E^{-\gamma_0}$, then after a sufficiently prolonged wandering in interstellar space they will have a spectrum $N_e(E) = KE^{-\gamma}$, where $\gamma = \gamma_0 + 1$. In the general case, when the escape of particles from the envelopes takes place all the time, intermediate results will naturally be obtained. It must also be considered that the field intensity is different in the shells and in the interstellar space, and consequently electrons of different energies will be responsible for radiation at a given frequency in both cases. For all these reasons, we are unable at present to draw from the similarity between the spectra of the sources and of the overall galactic radiation any conclusion concerning the secondary nature of the electrons in the halo. We can hope that further radio-astronomical observations (a study of the spectra as functions of the coordinates over a wide range of frequencies) will lead to a solution of this problem.

Thus, the question of the origin of the main part of the radio-emitting electrons in the galaxy remains open. At the same time, there are specific ways of solving this problem. It seems to us that a preliminary analysis of the available data indicates (in contradistinction to the statement made in reference 4, p. 431) that a secondary origin of the electrons is more probable.†

4. SOURCES OF COSMIC RAYS. MECHANISM OF ACCELERATION AND CHEMICAL COMPOSITION OF COSMIC RAYS

a) Sources of Cosmic Rays

One of the points which are extensively debated and which cause considerable disagreement is the question of the sources of cosmic rays. We can distinguish here between two principal points of view:

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*The adiabatic invariant changes also in nuclear collisions of cosmic rays, and for electrons in the case of bremsstrahlung. In magnetic bremsstrahlung of relativistic electrons, the friction force is in the direction of the momentum and the angle θ thus remains practically unchanged.

At high energies, the secondary electrons, which are produced in final analysis by nuclear collisions, move essentially in the direction of the incoming particle. However, with particles with energy $\varepsilon \sim 10^9$–10^{10} ev/nucleon, which are indeed the ones that give rise to the majority of the radiating electrons with energy 10^8–10^9 ev, we can assume apparently that the secondary electrons are more or less uniformly distributed over the angles θ, independently of the angular distribution of the primary protons and nuclei.

Let us emphasize again that the use of the invariant (3.11) presupposes an invariant particle energy. When applied to expanding shells this assumption, generally speaking, is incorrect. In this connection, if we speak of particles that leave the shell at later stages, there may be no reduction in $\sin\theta$, in view of the fact that in (3.10) the decrease in H is offset by the decrease in the momentum p.

*It must be borne in mind that the secondary electrons are also produced for the most part in the disk and in the central region, where the gas density is greater than the average density of the entire system.

†We note that the estimate (3.9) given here does not change even when the escape of the cosmic rays from the galaxy is significant. However, $U \sim 10^{39}$ to 10^{40} denotes here, as before, the energy loss due to nuclear collisions per unit time.

1. The cosmic-rays in the galaxy come essentially from supernovae and perhaps novae. Cosmic rays of metagalactic origin cannot play an important role in practice, and if they are significant, it is only at the highest energies, $\epsilon \gtrsim 10^{17}$ ev/nucleon. The cosmic rays produced in the sun and in the stars are essentially soft and play a secondary role in the overall energy balance, and also in the total flux of cosmic rays on earth. This is the position adopted in reference 1 (see also references 58, 59, 91, 102, and 110).

2. There is a great variety of important sources of cosmic rays, although sources of one particular type may play a predominant role in individual energy intervals. Thus, according to Cocconi,[114] the cosmic rays with energies $E \gtrsim 10^{15}$ ev are of metagalactic origin, while particles with energy $E < 10^{15}$ are accelerated by stars and as a result of flares of supernovae and novae. The non-flaring stars yield particles with energy $E \lesssim 10^{12}$ ev. A similar "hierarchy theory" is defended in an especially logical manner by Morrison,[3] who assumes, in addition, that the cosmic-ray sources in the halo and in the galactic spiral differ from each other to a great degree. This last conclusion is connected with the assumption of a certain degree of isolation of the spiral from the halo (the spiral and the halo are spoken of in reference 3 as being different "capture regions").

We wish to emphasize first that the difference between these two points of view is to a certain extent only quantitative and, what is important, this difference is of little importance in the solution of many other problems concerning the origin of cosmic rays. Nevertheless, the question of the sources is, naturally, quite important and we shall make a few remarks in this connection.

The existence of mechanisms which accelerate the cosmic rays can be considered as established on the sun, in the shells of supernovae, and in certain metagalactic nebulae (A Cygni, A Virginis, etc.). An analogy with supernovae, and also certain singularities in the spectrum of novae,[121] make it probable that the particles are very effectively accelerated by flares of novae, as has been assumed long ago (see references 58, 59, 64, and 1). In addition, the production of cosmic rays by processes that occur on so relatively quiet a star as the sun, gives every ground for assuming that the cosmic rays are produced also on most other stars. From many considerations we can assume also that the efficiency of generation of cosmic rays is particularly large in stars such as T Tauri and the like, and also in red giants and magnetic stars. However, only when it comes to stars like T Tauri and UV Ceti are there any experimentally-justified arguments for assuming that a large number of relativistic particles are actually produced within definite active periods. The point is that these stars exhibit clearly a non-equilibrium radiation with a continuous spectrum, which is connected with magnetic bremsstrahlung of relativistic electrons.[121] Were this observed radiation strongly polarized, its connection with the magnetic bremsstrahlung would be demonstrated in practice beyond any doubt. Indications of the presence of such polarization do exist, but serious doubts have also been raised recently. Therefore, so far as we can judge now, an exceedingly high acceleration efficiency of particles by stars of the T Tauri type cannot be considered proved.

More important is a second factor. Even if we assume that the different nonstationary stars accelerate the particles quite efficiently, this in itself is still no evidence in favor of the assumption that there are no separate principal sources of cosmic rays. Actually, the average power of the sun as a source of cosmic rays (with $\epsilon_k > 10^9$ ev/nucleon) does not exceed $10^{21} - 10^{22}$ erg/sec, whereas the total cosmic-ray energy in the galaxy should exceed $10^{39} - 10^{40}$ erg/sec [see (3.3)]. Therefore, as was already noted many times (see, for example, reference 1), if each of the 10^{11} stars in the galaxy were to radiate like the sun, they would as an aggregate deliver cosmic rays of energy $10^6 - 10^7$ times less than that necessary to maintain the quasi-stationary state. As regards the special very active stars, their number should be considerably less than that of all the stars. For example, even the relatively abundant magnetic stars in the galaxy number approximately 10^9, i.e., approximately 1% of the total number of stars.[122] The fields on such stars are stronger than the sun's field by a factor on the order of 10^3. Therefore the magnetic energy is greater than the solar energy by approximately 10^6 times; the activity of such a star, as a source of cosmic rays, is likewise not expected to exceed the sun's activity by more than 10^6 times. But for 10^9 stars this corresponds to a power of 10^{36} to 10^{37} erg/sec. Naturally, such an estimate cannot pretend to be convincing, but we see no particular grounds for expecting a greater rate of energy release, while a lower efficiency of acceleration by magnetic stars is quite possible. Stars of the T Tauri type (reference 121 and a private communication from I. M. Gordon) are sources of relativistic electrons with an average power of $10^{33} - 10^{34}$ erg/sec. The number of such stars in active state in the galaxy is, according to reference 123, equal to 5×10^4. This makes the power released $10^{38} - 10^{39}$ erg/sec. To show how large this power is, let us recall that the total power of the light radiated from the sun amounts to 3.86 $\times 10^{33}$ erg/sec. The thermal radiation from colder stars, such as T Tauri, is less than that from the sun, and thus the generation of cosmic rays (which consumes $10^{33} - 10^{34}$ erg/sec) will exceed the total radiated thermal power. Furthermore, even if the sources of fast electrons indeed had this power, it would still be unclear how much energy could be transferred to the nucleons of interest to us, with $\epsilon_k \sim 10^9$ ev/nucleon. It is natural to assume that this energy should amount to only a small fraction of the total energy release. But then either the power with which the nucleons of energy $\epsilon_k \gtrsim 10^9$ ev/nucleon are emitted is considerably less than 10^{33} to 10^{34} erg/sec, or the total power released in the cosmic rays is even substantially *greater than the given value* $10^{33}-10^{34}$ erg/sec, which in itself is exceedingly high.

Similar arguments lead us to the conclusion that different nonstationary stars should, in all probability, not give up to the cosmic rays (with $\epsilon_k \gtrsim 10^9$ ev/nucleon) more than $10^{36}-10^{37}$ erg/sec. The corresponding power released is more likely to be even less, i.e., *several orders of magnitude less than the* necessary 10^{39} to 10^{40} erg/sec. It must be noted that even Morrison assumes[3] a value of 10^{35} erg/sec for the power released by non-exploding stars in the region of the galactic spiral. But such a contribution can be significant only if the spiral is to some extent isolated, and this does not appear to be the actual case (see Sec. 2b).

We note also that the cosmic rays produced on the sun have an energy spectrum $N(\epsilon_k) = K\epsilon_k^{-\gamma}$, with $\gamma = 5$ to 6; such a spectrum of cosmic rays produced on the sun, even if we disregard energy considerations, is still no evidence in favor of assuming that the cosmic rays are essentially accelerated by non-exploding stars. In addition, we do not know whether the sun's cosmic rays contain a noticeable number of nuclei.

Arguments in favor of the fact that supernovae, and perhaps novae, can readily transfer $10^{39}-10^{40}$ erg/sec to cosmic rays, were already given in reference 1. We confine ourselves here to the remark that the latest data only strengthen this conclusion. Thus, the source A Cassiopeiae is on the order of 3000 parsec away and its power is 60 or 70 times greater than that assumed in reference 1. Estimates of the average power of the extragalactic supernovae have also been greatly raised, in connection with the increase taking place in the astronomical scale of distances. The total power released by many supernovae exceeds 10^{50} erg (see also reference 92), whereas a power of 10^{40} erg/sec is obtained if a flare is produced in the galaxy on the average by one supernova every 30 to 100 years, with (1 to 3) $\times 10^{49}$ erg going into cosmic rays. The possibility of such an efficiency, or of even a higher one, is confirmed by radio-astronomical data (see reference 1 and Table IV in Sec. 2b). If, on the other hand, all the radiation from the supernovae and novae has a magnetic-bremsstrahlung nature even at the time of the flare itself,[121] then a transfer of a considerable portion of the explosion energy to the cosmic rays is almost unavoidable. We note, finally, that cosmic rays with energies $E > 10^{12}$ ev can be considered as formed as a result of flares of supernovae also in the "hierarchy scheme."[3] But the chemical composition and also the conditions of injection and acceleration of the cosmic rays in the shells of the supernovae and by the non-exploding stars are, in all probability, quite different. Therefore, within the framework of the hierarchy scheme, one would expect a substantial change of both the energy spectrum and the chemical composition of the cosmic rays at a certain energy $E \sim 10^{12}$ ev. As far as we know, no such changes take place (see Sec. 1). To be sure, *the data on the chemical composition are still insufficient*, and the smooth energy spectrum still does not prove that the existing sources are predominantly of one type only.* But in order to forego any ideas concerning the predominating role of the supernovae in favor of the hierarchy scheme it is obviously necessary to tie the ends together with more *than just a certain degree of stretching.* For example, were the energy spectrum or the charged spectrum to change noticeably at $E \sim 10^{12}$ ev, this would at least be much more natural in the case of sources of two types. Since there exists no single fact clearly indicating a multiplicity of sources, we see no convincing evidence in favor of such an assumption. In other words, there are *still* no grounds for assuming it to be even probable that the non-exploding stars make a noticeable contribution to the flux of cosmic rays in the galaxy as a whole, or to the flux of cosmic rays on earth. More so, a similar assumption raises certain difficulties, primarily as regards the energy. On the other hand, there are no such objections to the assumption that the supernovae and novae play a predominant role (at $\epsilon \lesssim 10^{17}$ ev/nucleon).

b) Mechanisms of Acceleration and Energy Spectrum of Cosmic Rays. Possibility of Preferred Acceleration of Heavy Nuclei

In addition to acceleration due to electromagnetic processes, acceleration by means of shock waves has been under discussion recently. Usually the shock wave that arises upon collision of gas masses cannot lead directly to the production of relativistic particles. Thus, even at a gas velocity of 10^4 km/sec the energy of the particles amounts to only 0.5 Mev/nucleon. Such shock waves can at best play a role of "injectors" of fast particles, which are accelerated later on by some other mechanism. However, under special conditions, such as the propagation of very strong shock waves in a medium with decreasing density, their role can be more substantial.

Colgate and Johnson[124] undertook a qualitative analysis of the process of formation of relativistic particles in the explosion of a supernova. The corresponding estimates are based on the assumption that instability with respect to the transition into a degenerate electron state causes an energy on the order of 10^{51} erg to be liberated in the star, within a short time, in the form of radiation of temperature ~ 1 Mev.

*Another possible argument in favor of the existence of certain single-type dominating sources is connected with the character of the high-latitude cutoff.[47] It can be said here, too, that the available data do not yield any evidence in favor of multiplicity of the sources, although they do not refute this possibility.

The pressure of this radiation produces a spherical shock wave, which is accelerated on going into the less dense surface layers. Starting with a density ~ 10 g/cm^3, the motion becomes relativistic and the entire layer of matter above it is converted into cosmic rays with an energy spectrum which is determined by the dependence of the density on the radius, and with the same composition as the external layers of the star. The maximum energy of the particles, $\sim 10^{17}$ ev/nucleon, is obtained if the acceleration continues to a level with a density $\sim 10^{-7}$ g/cm^3, and with enough matter above it (~ 3 g/cm^2) to maintain the radiation.

In view of the absence of any detailed calculations, it is still difficult to judge whether this scheme can explain the basic properties of cosmic rays. It must nevertheless be noted that reference 124 uses the Thomson cross section $\pi r_0^2 = 6 \times 10^{-26}$ cm^2 to determine the range of the photons. This is utterly incorrect, since it is assumed that the energies of the photons ahead of the shock wave reach 10^{13} ev during the last stage. The absorbtion of photons with this energy calls for approximately 20 radiation length, which for hydrogen amounts to approximately 10^3 g/cm^2, instead of the employed 3 g/cm^2. Therefore the radiation will "break through" the shell of the star much sooner than estimated in reference 124, and the maximum energy of the accelerated particles will be several orders of magnitude lower. In addition, when the photons have a long range, the role of the nuclear photoeffect, which is entirely disregarded in reference 124, will increase significantly. Photodisintegration will reduce the number of heavy nuclei among the accelerated particles. It is clear therefore that the question of acceleration by means of shock waves needs a more detailed analysis. We can assume tentatively that this mechanism is more suitable for injection, that is, for the production of the particles, which are subsequently accelerated by some electromagnetic mechanism.

The action of the electromagnetic acceleration mechanisms is based on the fact that the electric field induced in the medium by the increase in the magnetic field always performs positive work on the charges that move in this field. There are two principal modifications of electromagnetic acceleration mechanisms: betatron acceleration in a homogeneous magnetic field that increases with time,[125] and acceleration of particles by head-on collisions with moving inhomogeneities of the magnetic field.[126] All the other known acceleration mechanisms either reduce to one of these types, or are a combination of the two.

In the betatron acceleration the longitudinal (relative to the magnetic field) component of the particle momentum, $p_{\parallel}$, is constant, while for the transverse component $p_{\perp}$ we have from the adiabatic invariant (3.10) $p_{\perp}^2 \sim H$. Expressing H in terms of the radius of the Larmor orbit of the particle $r = cp_{\perp}/eZH$, we obtain $p_{\perp}^2 \sim 1/r^2$ and $H \sim 1/r^2$. Thus, an increase in the momentum or in the magnetic field is associated with a shrinking of the Larmor orbit of the particles. For an ionized gas this is equivalent to a transverse compression of the gas. In such a compression the volume per particle is $V \sim r^2$, and consequently $p^2 \simeq p_{\perp}^2 \sim 1/V$, where we neglect the invariant longitudinal component of the momentum (for a cylinder $V = \pi r^2 l$, where the length l remains invariant under the considered transverse compression). Consequently the kinetic energy of the particle is connected with the volume occupied by the particle by the relation

$$E_k \propto \frac{1}{V^{\gamma-1}}, \qquad (4.1)$$

where $\gamma = 2$ for unrelativistic energies ($E_k \sim p^2$)[127] and $\gamma = 3/2$ for ultrarelativistic energies ($E_k \simeq E \sim p$). Relation (4.1) corresponds at the indicated values of γ to the usual law of adiabatic compression for particles with two degrees of freedom.

When the magnetic field returns to its initial value, the particles are slowed down to their initial velocities. The process is fully reversible and therefore if the magnetic field in the medium remains at an average constant level, then the average particle energy remains unchanged. The resultant acceleration takes place if the field is inhomogeneous and the particle has a chance to leave the region of the increasing field before the field starts to decrease.[125] The particle is also accelerated if its energy is redistributed between $p_{\parallel}$ and $p_{\perp}$ as a result of collisions with the inhomogeneities of the field.[128,129] In the latter case, after each collision (at $t = t_i$) we have, on the average, $p_{\perp}^2(t_i) = \frac{2}{3}p^2(t_i)$ and $p_{\parallel}^2(t_i) = \frac{1}{3}p^2(t_i)$. If the next collision takes place after a time interval τ, then

$$p^2(t_i+\tau) = \frac{1}{3}p^2(t_i) + \frac{2}{3}p^2(t_i)\frac{H(t_i+\tau)}{H(t_i)} = \frac{1}{3}p^2(t_i)\left[1 + 2\frac{H(t_i+\tau)}{H(\tau_i)}\right],$$

since, according to (3.10), only $p_{\perp}$ changes. Let the frequency be twice the frequency of the oscillations of the magnetic field at $H(t_i + \tau) = H + \Delta H$, $H(t_i + 2\tau) = H(t_i) = H$; then, over a complete cycle of the field, the change in the momentum will be

$$p^2(t_i+2\tau) = \frac{1}{3}p^2(t_i+\tau)\left[1 + 2\frac{H(t_i+2\tau)}{H(t_i+\tau)}\right] \simeq \frac{1}{9}p^2(t_i)\left[9 + 2\left(\frac{\Delta H}{H}\right)^2\right].$$

Hence

$$\Delta p^2 \simeq \frac{2}{9}\left(\frac{\Delta H}{H}\right)^2 p^2. \qquad (4.2)$$

In the general case of arbitrary collision statistics, the increment in the square of the total momentum, as in (4.2), is a second-order difference effect in the amplitude of the field oscillations, whereas the change during one half cycle is an effect of order $\Delta H/H$.

The second class of accelerating mechanisms, namely acceleration by collision with moving inhomo-

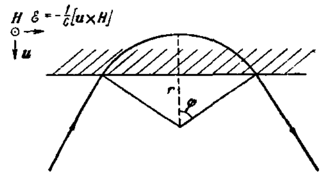

FIG. 5

geneities of the magnetic field, is simplest to analyze by analogy with collisions with a moving solid wall. From the conservation of energy and momentum we readily find that the increase in the total energy E in one collision is (see references 126 and 1)

$$\Delta E = -\frac{2E}{c^2}(\mathbf{u}, \mathbf{v}), \qquad (4.3)$$

where the wall velocity **u** is assumed small compared with the particle velocity **v**.

We note that in a collision with a magnetic inhomogeneity, the acceleration is obviously caused, in final analysis, by the induced electric field $\mathscr{E} = -(1/c)\mathbf{u} \times \mathbf{H}$, which is due to the transfer of the magnetic field "frozen-in" the medium at a velocity u. In fact, the change in the energy of the particle after reflection from the moving magnetic "wall" (see Fig. 5) is precisely equal to the expression (4.2):

$$\Delta E = eZ \int \mathscr{E}\, ds = 2eZr\mathscr{E} \sin\varphi = 2eZ \frac{uH}{c} \frac{Ev_\perp}{eZHc} \sin\varphi = -\frac{2E}{c^2}\mathbf{uv}.$$

Here we took into consideration the fact that the radius of the curvature is $r = Ev_\perp/eZHc$.

In the case of spiral motion of a particle along a contracting tube of magnetic force lines, the transverse component of the momentum first increases (as in betatron acceleration, owing to the increase in the magnetic field), but decreases to the initial value after reflection. A finite change is produced (if the tube moves) only in the longitudinal component of the momentum, which experiences precisely the reflection referred to above.

If the particle experiences only head-on collisions, i.e., it is located between two approaching magnetic "walls," then its energy changes in accordance with the law of adiabatic compression (4.1), as in betatron acceleration. However, only one degree of freedom of the particles is important here, and therefore in (4.1) $\gamma = 3$ for nonrelativistic energies[127] and $\gamma = 2$ for relativistic ones. In fact, over a time $\Delta t = 2l/v_\perp$, where l is the distance between the walls and $v_\perp$ is the normal component of the velocity, the increase in energy is equal to (4.3). Therefore

$$\frac{dE}{dt} = \frac{\Delta E}{\Delta t} = \frac{2E}{c^2} v_\perp^2 \frac{u}{2l} = -\frac{Ev_\perp^2}{c^2}\frac{1}{l}\frac{dl}{dt}.$$

The fact that $u = -dl/dt$ is also taken into account here. Neglecting the component $v_\parallel$ which remains unchanged during the acceleration, and taking into consideration the relation $E^2v^2/c^2 = c^2p^2$, we obtain after integration $p^2 \sim 1/l^2 \sim 1/V^2$ ($V \sim l$ in the one-dimensional compression considered here). Thus the increase in the particle energy is determined in this case simply by the adiabatic compression of the medium.

In such a systematic acceleration, the increase in energy is limited, since the particle cannot be squeezed into a space in the magnetic field of the "walls" with dimensions smaller than the particle radius of curvature. Therefore, although the systematic acceleration can indeed be significant at the initial stage of the particle acceleration,[130] acceleration to high energies can be realized, apparently, only by the statistical mechanism (3.8) (see references 126 and 1). In the statistical acceleration the particle experiences both head-on collisions, by which its energy is increased, and "overtaking" collisions, in which the particle loses energy. Owing to the great probability of the head-on collisions, the particle energy is increased on the average by an amount which is a differential effect of second order in u/v, whereas the relative increment in the energy during one collision is proportional to u/v.

Thus, an analysis of the electromagnetic mechanisms of acceleration leads to the conclusion that these mechanisms, firstly, can ensure a relatively fast but limited systematic acceleration, which, in the case of cosmic rays, reduces in all known cases simply to adiabatic heating of the gas as it is compressed; secondly, a slower statistical acceleration is possible, which can act during the entire lifetime of the particle. For a systematic acceleration of a particle from thermal energies $\sim$ 1 to 10 ev ($\simeq 10^4$ to 10^5 deg K) to relativistic energies $\sim$ 1 to 10 Bev, even in the most favorable case, $\gamma = 3$ in (4.1), the medium must be compressed by a factor of $10^4 - 10^5$. Such a compression is little likely under real astrophysical conditions, and it is therefore natural to assume that the particles acquire relativistic energies by statistical acceleration.

Let us proceed now to the question of the spectrum of the cosmic rays. From the experimental data (see Sec. 1b) it follows that the energy spectrum of the cosmic rays is characterized, over a very broad energy interval, by a power-law dependence on the energy, with an exponent $\gamma = 2.5$, which is the same for different nuclei. A power-law energy spectrum can be obtained (see references 126, 131, and 1) under the following assumptions: a) the particles are accelerated in accordance with the law (3.8), which ensures an exponential increase of the energy with time; b) the probability that the acceleration of a given particle continues during a time interval t is

$$w(t) = \frac{1}{T} e^{-\frac{t}{T}},$$

where T is the average acceleration time. In the initial Fermi theory[126] it was assumed that T is the average lifetime relative to the nuclear collisions. This, however, leads to a strong dependence of the nuclear spectrum on the atomic weight, in disagreement with the observations. In this connection, we now take for T the average time of diffusion escape of the cosmic rays from the acceleration region (see references 131 and 1). Finally, when the spectrum of cosmic rays is evaluated, it is usually assumed that: c) the acceleration conditions are stationary at least during the time necessary for the particle to acquire the maximum observed energy. In other words, the parameters α and T are constant, and the injection of the particles is uniform over a time $t \gtrsim \frac{1}{\alpha}\ln(E_m/E_0)$, where E_m is the maximum energy and E_0 the initial energy.

These assumptions lead directly to a differential energy spectrum of accelerated particles (see reference 1)

$$N(E)\,dE = KE^{-\gamma}\,dE, \quad \gamma = 1 + \frac{1}{\alpha T}. \qquad (4.4)$$

Thus, for a definite choice of the quantities α and T, we can obtain the necessary value of γ. However, the rather stringent assumptions made in the derivation of the spectrum (4.4), and the strong dependence of γ on the specific values of α and T, are to some extent unsatisfactory. Actually, the exponent γ is close to 2.5 in this scheme only by accident, particularly if we take it into account that α and T are not related to each other and vary over a wide range for different cosmic objects.

It would be more natural to assume that the form of the energy spectrum of the cosmic rays, and their origin as a whole, are a fundamental property of the dynamics of a turbulent magnetized plasma on a cosmic scale. Unfortunately, the dynamics of such a plasma has been little studied so far. Nevertheless, there exists a simple possibility[132] of obtaining a cosmic-ray spectrum which is close to that observed, by assuming that the energy is uniformly distributed between the kinetic energy of turbulent motion, the magnetic field, and the cosmic rays (we speak here of the distribution in the state of quasi-stationary equilibrium of cosmic plasma). Indeed, we assume that a turbulent magnetized plasma contained within a certain bound volume tends to a quasi-equilibrium state, in which the total energy W is uniformly distributed among the turbulent motion, the magnetic field, and the cosmic rays. Then the energy of the cosmic rays in the volume under consideration will be

$$W_c = n\overline{E}_k = \tfrac{1}{3}W, \qquad (4.5)$$

where n is a number of cosmic-ray particles in the volume under consideration, and $\overline{E}_k$ is their average kinetic energy (we shall henceforth consider the region of ultrarelativistic energies, when $E_k \simeq E$).

The specific mechanism by which such a quasi-equilibrium is established is still unclear, although certain ideas have been expressed on this subject.[133] We shall assume furthermore that the energy of the system diminishes principally by leakage of relativistic particles from the considered volume. As a specific example, we can take, for example, a nebula with a vigorous turbulent motion produced during the flare of a supernova. Under the indicated assumptions, the condition for the energy balance has the form

$$\overline{E}\,dn = dW = d\,(3n\overline{E})$$

or $\overline{E}\,dn = -\frac{3}{2}n\,d\overline{E}$, where $\overline{E}\,dn$ is the energy of the cosmic rays leaving the nebula. Consequently, the number of cosmic-ray particles in the nebula, as a function of their average energy, is

$$n = \mathrm{const}\,\overline{E}^{-1.5}, \qquad (4.6)$$

and the differential energy spectrum of the particles leaving the nebula has the form

$$N(E)\,dE = -dn = \mathrm{const}\,E^{-2.5}\,dE, \qquad (4.7)$$

where replacement of the mean energy $\overline{E}$ by the true energy E is obviously valid if the spectrum of the cosmic rays in the nebula is close to monochromatic. It can be shown[134] that under natural assumptions the spectrum (4.7) is produced for any spectrum of cosmic rays inside the nebula, if the latter varies with time only as a result of the acceleration of particles, in accordance with the arbitrary law $E(t) = E(0)\varphi(t)$.

Thus, independently of the character of the acceleration and of the spectrum of the cosmic rays inside the nebula, the particles leaving the nebula have an energy spectrum (4.7). The possibility of obtaining an energy spectrum of cosmic rays in the region $E \gg Mc^2$, subject only to the assumption (4.5), together with the available data that favor the near-equality of cosmic-ray energy to the turbulent and magnetic energy in the galaxy and in certain nebulae, makes it particularly necessary to analyze theoretically the conditions under which relation (4.5) is satisfied.

Let us dwell now in greater detail on the initial stage of the acceleration of the particles and the associated injection problem. This problem is important because the initial stage of acceleration determines to a considerable extent one of the most characteristic properties of cosmic rays — their chemical composition. As is well known (see Sec. 1a), a considerable excess of heavy nuclei over the natural abundance is observed in cosmic rays. To explain this fact it is apparently necessary to assume a preferred acceleration of heavy elements in the cosmic-ray sources (see Sec. 4b). At the same time, the customary analysis (see references 126 and 1) shows that, generally speaking, the acceleration of heavy multiply-charged ions is made quite difficult by the large energy losses due to collision and ionization in the medium. This difficulty is eliminated after a more detailed analysis[135] of the effect of the energy losses on the acceleration of the particles in the nonrelativistic region. The point is that the existence of a maximum of energy losses due

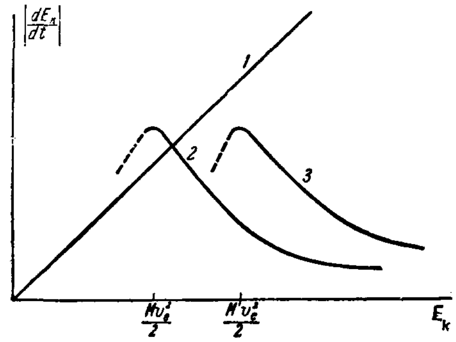

FIG. 6

to collision and ionization, at a particle velocity close to the velocity of the electrons in the retarding medium, makes possible an "injectionless" acceleration of particles from thermal energies, provided the rate at which energy is acquired during the acceleration process is sufficiently high. With increasing mass of the particle, fewer demands are made of the acceleration mechanism: for the same rate of acceleration, the injection threshold may be sufficiently high for light nuclei and considerably lower for the heavy ones. This is seen qualitatively in Fig. 6, where the axes represent the particle energy and the absolute value of the rate of acquisition (Curve 1) or loss (Curves 2 and 3) of energy. For simplicity we assume the following variation of energy here

$$\frac{dE_k}{dt} = \alpha E_k. \tag{4.8}$$

This is realized, for example, in betatron acceleration (E_k is the kinetic energy). The energy lost to collisions and ionization, at a particle velocity $v \gg v_e$ (v_e is the velocity of the electron in the retarding medium) is given by

$$-\frac{dE_k}{dt} = \frac{4\pi e^4 Z^2 nL}{mv}, \tag{4.9}$$

where eZ is the particle charge, m is the electron mass, and L is a logarithmic factor that depends weakly on the particle velocity. The maximum loss occurs at $v \simeq v_e$, and we can use approximately the same expression (4.9) to estimate the loss at the maximum. For particles with masses M and M′ and for equal initial ionization,* the loss curves will have approximately the same value at the maximum, but the curve for particle with mass $M' > M$ will be shifted by a factor M′/M to the right (Curves 2 and 3 of Fig. 6) and may not intersect the energy-intake curve. Since the point of intersection determines the injection energy, the heavier particles will become accelerated without injection, i.e., independently of their initial energy, whereas the presence of an injection threshold makes the acceleration of the latter particles difficult.

Analogous arguments can be made also for an arbitrary mechanism of acceleration, and account can also be taken of the effect of the loss of electrons by the particle as its velocity is increased. In particular, reference 135 gives for the statistical Fermi acceleration the following two limiting expressions for the critical value of the parameter $\alpha = u^2/cl$: if the charge of the particle is conserved during the process of acceleration

$$\alpha_k(A) = \frac{4\pi n e^4 Z^2 L}{mcv_e^2 M} = \alpha_k(p)\frac{Z^2}{A}; \tag{4.10}$$

if an equilibrium charge $Z = Z_0^{1/3}(v/v_0)$ can be established during each instant of time (z_0 is the atomic number of the element and $v = e^2/\hbar$), we have

$$\alpha_k(A) = \alpha_k(p)\left(\frac{v_e}{v_0}\right)^2 \frac{Z_0^{2/3}}{A}. \tag{4.11}$$

The parameter α_k is so defined that "injectionless" acceleration will take place when $\alpha > \alpha_k(A)$ for all nuclei with atomic weights greater than or equal to A. At a medium density $n = 10^3$ cm^{-3} and a temperature 10^5 deg K, the values of α_k, calculated from (4.10) and (4.11), are respectively 0.58×10^{-9} and 1.2×10^{-9} for iron, whereas, under the same condition, $\alpha_k(p) = 8.1 \times 10^{-9}$ for hydrogen.[136] As shown in reference 1, such values of the parameter α can be reached in the shells of supernovae.

Naturally, there are no grounds for assuming that the values of α lie, by accident, precisely within the required limits. However, if α was sufficiently large at the initial instant, say immediately after the flare-up of a supernova, then injectionless acceleration of all the nuclei of the shell leads to a rapid dissipation of the turbulent motion and to a corresponding reduction in α until only a relatively small number of heavy elements can be accelerated.

If it is nuclei that become predominantly accelerated in the sources, these will be the particles with the largest energies, a very favorable factor. In fact, the maximum observed energy of a primary particle, $E \sim 10^{19}$ ev, corresponds in this case to an energy $\epsilon \sim 10^{17}$ ev/nucleon and, what is most important, to a radius of curvature

$$r = \frac{E \sin\theta}{300ZH} \simeq \frac{\varepsilon \sin\theta}{150H} \simeq 0.1 \text{ parsec}$$

in a field $H \sim 10^{-3}$ oe and at $\sin\theta \simeq 1/3$. At the same time, there is a limit on the production of high energies by statistical acceleration, determined by the escape of the particles from the system. The radius of the source A Cassiopeiae amounts at present to $R \simeq 2$ parsec, and the maximum possible field H_{max} is greater than 10^{-3} oe. Thus, even when $\epsilon \simeq 10^{17}$ ev/nucleon, the condition $r \ll R$, which is necessary for the acceleration, can be fulfilled in the shells, together

*It is assumed here that the temperature (and consequently the degree of ionization of the gas) is not too large in the acceleration region ($T \simeq 10^4$ to 10^5 deg K, $Z \simeq 1$ to 2). If the ionization is nearly complete, as can take place in the case of injection by strong shock waves or when the gas is ejected from the internal regions of the star, then the strong dependence of the losses (4.9) on Z makes the acceleration of heavy nuclei practically impossible.

with the more stringent requirement $r \ll l \lesssim L$, where l is the characteristic dimension of the inhomogeneities of the magnetic field.

c) Transformation of the Chemical Composition of Cosmic Rays in the Interstellar Medium

One of the main problems of the theory of the origin of cosmic rays is the interpretation of the data concerning their chemical composition near the earth. This composition is determined by three factors: the initial composition of the elements of the source, the conditions for the acceleration of the different elements in the source to relativistic energies (these two factors determine the composition of the cosmic rays in the source), and finally the transformation of the nuclei upon collision in interstellar gas along the path from the source to the earth. The data which we have at the present are insufficient for an unequivocal estimate of the relative role of these factors in the formation of the observed composition. Nevertheless, it is useful to analyze this problem in greater detail on the basis of the concepts developed above.

We start with the question of the transformation of the chemical composition of the cosmic rays in the interstellar medium. For this purpose, naturally, it is necessary to specify a definite model of the abundance of cosmic rays in the galaxy. We shall consider below two models, which are actually two opposite extreme cases. The first is the diffusion model, in which the sources are assumed concentrated in a certain region (say in the center of the galaxy) and the motion of the cosmic rays is assumed to be a random process with a certain isotropic coefficient of diffusion $D(\mathbf{r})$. The equations for the concentration $N_i(\mathbf{r}, t)$ of the nuclei of type i are in this case (see reference 1)

$$\frac{\partial N_i}{\partial t} - \operatorname{div}(D\nabla N_i) + \frac{N_i}{T_i} = Q_i(\mathbf{r}, t) + \sum_{k<i} p_{ki}\frac{N_k}{T_k}, \quad (4.12)$$

where $Q_i(\mathbf{r}, t)$ is the source density, p_{ki} is the "fragmentation probability," i.e., the average number of nuclei of group i, produced upon absorption of a nucleus of group k, and T_i is the average lifetime with respect to absorption. In (4.12) and henceforth, the index $i = 1$ corresponds to the group of the heaviest of the nuclei considered.

The second of these models, "regular" fragmentation, corresponds to the motion of cosmic rays along a definite path, for example, strictly along the magnetic force lines. The concentration $N_i^{(p)}(s)$ at a distance s (in g/cm^2) from a stationary source, in which the concentration is equal to q_i, is then determined by the equation

$$\frac{dN_i^{(p)}}{ds} + \frac{N_i^{(p)}}{\lambda_i} = \sum_{k<i} p_{ki}\frac{N_k^{(p)}}{\lambda_k}; \quad N_i^{(p)}(0) = q_i. \quad (4.13)$$

It is assumed here, obviously, that all the particles along the path from the source to the point of observation pass through one and the same thickness of matter, s. If we introduce the time t of motion of the particles from the source to the point under consideration (the same for all particles) and recognize that $s = \rho ct$ (ρ is the density of the medium, and c is the particle velocity, which is equal to the velocity of light) and that the mean free path is $\lambda_i = \rho c T_i$, then (4.13) can be rewritten in another, equivalent form

$$\frac{dN_i^{(p)}}{dt} + \frac{N_i^{(p)}}{T_i} = \sum_{k<i} p_{ki}\frac{N_k^{(p)}}{T_k}; \quad N_k^{(p)}(0) = q_k. \quad (4.14)$$

Equations (4.14) coincide formally with (4.12) when $D = 0$ and $Q_i = Q_i(t) = q_i\delta(t)$.

Unlike the diffusion model, the "regular model" does not correspond to the picture of cosmic-ray motion outlined in Sec. 3c. However, one might think that a relatively slight modification of this model could lead to an actual mixing of the cosmic rays in the galaxy and thereby lead to agreement with the available data. At the same time, the regular model differs particularly strongly from the diffusion model, and therefore the analysis is very useful for comparison purposes. The question of the applicability of these models, and the entire problem of determining the chemical composition of cosmic rays, will be discussed in Sec. 4d.

We shall dwell here only on the solution of Eqs. (4.12) — (4.14) and on the choice of the parameters p_{ik} and T_k.

The solution of (4.13) and (4.14) is readily obtained first for $i = 1$, and then, by the method of induction, for any i:

$$N_i^{(p)} = \sum_{k=1}^{i} a_{ik} e^{-\frac{t}{T_k}} = \sum_{k=1}^{i} a_{ik} e^{-\nu_k s}. \quad (4.15)$$

Here $\nu_k = 1/\lambda_k$ where λ_k is the absorption range and the coefficients a_i are determined by the recurrence relations

$$a_{ik} = \frac{1}{\nu_i - \nu_k} \sum_{k\leqslant j<i} \nu_j p_{ji} a_{jk}, \quad a_{ii} = q_i - \sum_{k=1}^{i-1} a_{ik}. \quad (4.16)$$

With the aid of (4.15) we can obtain a solution for a broad class of problems, in which the sources are arbitrarily distributed in space and in time, and the particles arrive at the point of observation along various paths. The only assumption is that all the sources are characterized by one and the same composition. In fact, if $G(t)$ is the distribution (which is the same for all types of particles) over the time elapsed from the instant when the particles are accelerated to the instant of arrival at the point under consideration, then the composition observed at this point, as was noted in reference 109, is given by the expressions

$$N_i = \int_0^\infty N_i^{(p)}(t)\, G(t)\, dt = \sum_{k\leqslant 1} a_{ik} \int_0^\infty e^{-\frac{t}{T_k}} G(t)\, dt. \quad (4.17)$$

The solution of the diffusion equations (4.12) also reduces to the form (4.17). This can be readily shown, in particular, for the stationary diffusion considered below, when $\partial N_i/\partial t = 0$, $G_i = Q_i(\mathbf{r})$, and (4.12) assumed the form

$$\operatorname{div}(D\nabla N_i) = \frac{N_i}{T_i} - Q_i(\mathbf{r}) - \sum_{k=1}^{i-1} p_{ki}\frac{N_k}{T_k}. \qquad (4.18)$$

Let the distribution of the sources for all types of nuclei be the same, i.e., let $Q_i(\mathbf{r}) = q_i\chi(\mathbf{r})$, and let the function $G(\mathbf{r}, t)$ satisfy the equation

$$\frac{\partial G}{\partial t} - \operatorname{div}(D\nabla G) = 0, \qquad (4.19)$$

the necessary boundary conditions, and the condition $G(\mathbf{r}, 0) = \chi(\mathbf{r})$. Let, furthermore, $N_i^{(p)}$ be solutions of (4.14) with given values of q_i. Then the function

$$N_i(\mathbf{r}) = \int_0^\infty N_i^{(p)}(t)G(\mathbf{r}, t)\,dt = \sum_{k=1}^{i} a_{ik}F_k(\mathbf{r}), \qquad (4.20)$$

where

$$F_k(\mathbf{r}) = \int_0^\infty e^{-\frac{t}{T_k}} G(\mathbf{r}, t)\,dt, \qquad (4.21)$$

is the solution of Eq. (4.18) with the same boundary conditions, as can be verified by direct substitution.

If one of the functions $F_k(\mathbf{r})$ is known, for example, $F_1(\mathbf{r})$, then, as can be readily seen from (4.21), any other function can be obtained simply by substituting T_1 for the corresponding T_k. Therefore, in each specific problem it is enough to determine one of these functions. This is done most simply by solving (4.18) for the group of heaviest nuclei ($i = 1$), for in this case the last term in the right half of (4.18) vanishes.

Let us carry out the solution for a point source, located in the center of a spherical region of radius R, with a general boundary condition for the flux on the surface of the sphere

$$-D\frac{\partial N_i}{\partial r} = \beta\frac{D}{R}N_i \quad (\text{for } r = R). \qquad (4.22)$$

This solution is

$$F_i(r) = \frac{1}{4\pi Dr}\,\frac{(\varkappa_i - 1 + \beta)\,e^{\varkappa_i\left(1-\frac{r}{R}\right)} + (\varkappa_i + 1 - \beta)\,e^{-\varkappa_i\left(1-\frac{r}{R}\right)}}{(\varkappa_i - 1 + \beta)\,e^{\varkappa_i} + (\varkappa_i + 1 - \beta)\,e^{-\varkappa_i}}, \qquad (4.23)$$

where

$$\varkappa_i = \frac{R}{\sqrt{DT_i}}, \qquad (4.24)$$

and β is a dimensionless parameter characterizing the conditions under which the particles leave the volume under consideration. Thus, the case $\beta = 0$ corresponds to total reflection of the particles on the boundary. When $\beta = \infty$, the expression (4.23) is a solution for the absorbing boundary. In the case of slow leakage of particles ($\beta \ll 1$) the parameter β is expressed in terms of the average time of escape of the particles T_e from the volume under consideration

$$\beta = \frac{R^2}{3DT_e}, \qquad (4.25)$$

Since the flux per unit surface [see (4.22)] is in this case

$$\frac{\frac{4}{3}\pi R^3 N_i}{4\pi R^2 T_e} = \frac{R}{3T_e}N_i.$$

If the boundary is sufficiently far away, for instance $R \gg r$ and $R \gg \sqrt{DT_i}$), then the solution of (4.23) coincides with the solution for a point source in unbounded space

$$F_i(r) = \frac{1}{4\pi Dr}e^{-\frac{r}{\sqrt{DT_i}}}. \qquad (4.26)$$

Finally, in the inverse case, when $R \ll \sqrt{DT_i}$ (more accurately, $R^2/DT_i \ll r/R$) and the escape of particles is small ($\beta \ll 1$), we obtain from (4.23)

$$F_i = \left[\frac{4}{3}\pi R^3\left(\frac{1}{T_i} + \frac{1}{T_e}\right)\right]^{-1} = \frac{T_i'}{\frac{4}{3}\pi R^3}; \quad \frac{1}{T_i'} = \frac{1}{T_i} + \frac{1}{T_e}. \qquad (4.27)$$

As $T_e \to \infty$ this solution corresponds to the so-called equilibrium composition, which occurs when all the sources are uniformly distributed in space with a density $q_i/(4\pi R^3/3)$. If we take as q_i in (4.16) the intensity of the sources per unit volume, then

$$F_i = T_i. \qquad (4.27a)$$

To determine variation of the composition as the cosmic rays move from the source, we must, in addition to choosing a definite model for the diffusion of the cosmic rays in the galaxy, know also the absorption ranges and the fragmentation probabilities for different charge groups of the cosmic-ray nuclei. The values of the fragmentation probabilities, obtained from measurements with the best statistics reached to date, are listed in Table VI, where p_{ik}' and p_{ik} are the fragmentation probabilities,* referred respectively to the interaction range and to the absorption range of the nuclei of group i.

The first row in Table VI contains the results of reference 137. The later results[138] are given in the second row. These values must apparently be considered as the best available at present.

TABLE VI

		$H \to H$	$H \to M$	$H \to L$	$H \to \alpha$
p_{ik}'	137	0.30±0.12	0.35±0.15	0.11±0.09	1.9 ±0.38
	138	0.32±0.08	0.46±0.09	0.09±0.04	1.37±0.17
p_{ik}	(a)	—	0.7	0.1	2.0
	(б)	—	1.0	0.0	3.5
		$M \to M$	$M \to L$	$M \to \alpha$	$L \to \alpha$
p_{ik}'	137	0.06±0.06	0.38±0.11	1.57±0.25	—
	138	0.14±0.04	0.32±0.05	1.27±0.11	—
p_{ik}	(a)	—	0.40	1.5	1.5
	(б)	—	0.40	2.0	1.5

*In order to understand clearly the character of the progress made in the determination of the quantity p_{ik}, we note that reference 1 gives values $p_{ML}' = 0.23$ to 0.42 and $p_{HL}' = 0.23$ to 0.48.

It is especially important for what is to follow to determine the probabilities of the production of the nuclei of group L from the heavier ones, i.e., the coefficients p_{HL} and p_{ML}. In this respect, it is very significant that the probability p'_{ML} given by reference 138 is in good agreement with the results of reference 139, where a direct investigation was made of the disintegration of carbon nuclei by 1.66-Bev protons in an accelerator. According to reference 139, the cross section for the direct production of L nuclei from carbon is 63 mb, while the total absorption cross section is 227 ± 12 mb, hence $p'_{CL} = 0.28$. In addition, the cross sections for the production of radioactive nuclei C^{10} and C^{11}, from which boron is produced by β decay, is 31 mb. Therefore, the total cross section for the production of L nuclei in the interaction between protons and nuclei of carbon is 94 mb, and the corresponding probability is $p_{C,L} = 0.41$. The production of lithium nuclei in β decay of He^6 can be disregarded, since the cross section for the production of He^6 amounts to only about 1 mb.[140]

On the other hand, it must be taken into account that the values p'_{ik} in the second row of Table VI pertain to the interaction range, and a recalculation to the absorption range λ_i is carried out by means of the formulas

$$\lambda_i = \frac{\lambda_{\text{int}, i}}{1 - p'_{ii}}, \quad p_{ik} = \frac{p'_{ik}}{1 - p'_{ii}} \tag{4.28}$$

(the indices 1, 2, 3, 4, and 5 correspond to the groups H, M, L, α, and p). The subsequently-adopted values of p_{ik} (variant a) are given in the third row of Table VI. They were calculated from the data of reference 138 (second row of Table VI) with the aid of Eq. (4.28), and the corresponding absorption ranges are given in the last column of Table V.

It is also important to note that the probability p_{HL} is, according to references 137 and 138, very small. This means that the L nuclei are formed principally from the heavier nuclei with neighboring atomic weights, which lose several protons or α particles, while the direct production of nuclei of group L from the very heavy nuclei plays practically no role at all. Therefore, under conditions when the composition of the cosmic rays differs from that observed on earth in having an excess of heavier nuclei, the probability p_{HL} should be even less. In this case it is incorrect to use the absorption range and the fragmentation probabilities determined for group H on earth. In fact, the group H ($Z \geq 10$) includes a broad interval of atomic weights, and if its composition changes substantially along the path from the source (for example, if this group consists only of VH nuclei), then the effective absorption range and the fragmentation probabilities will depend on the distance from the source, and can differ considerably from those assumed. A more exact analysis calls for introducing instead of the H group several subgroups of nuclei with nearly equal atomic numbers. However, the lack of data on the fragmentation probabilities in hydrogen for such groups does not permit such a generalization at present. In order to take into account possible differences of the values p_{ik} from the observed values in the case when the sources produce essentially very heavy nuclei, Table VI gives also a somewhat modified set of p_{ik} (variant b), in which, in accordance with the preceding, the value of p_{HL} has been reduced, and the coefficients p_{HM}, $p_{H\alpha}$, and $p_{M\alpha}$ have been increased.

d) Discussion of the Chemical Composition of Cosmic Rays

The extremely small abundance of nuclei of group L (Li, Be, B) *in the universe* allows us to assume that* these nuclei are not formed directly in the cosmic-ray sources, but are exclusively products of disintegrations of the heavier M and H nuclei. We can then estimate from the number of L nuclei observed on earth the thickness of matter traversed by the cosmic rays, or some other equivalent parameter of the model, for example the ratio of the coefficient of diffusion to the average concentration of the gas. It will be useful to employ henceforth, for diffusion models, the parameter $\xi = 10^{-30}$ D/n, which, if specified, together with the known average distance to the sources (assumed to be the distance from the sun to the center of the galaxy), determines the problem completely. Thus, assuming that *there are no L nuclei in the source, we can determine* from the composition observed on earth, the required composition of the sources for different models. We note that the assumption that all or part of the L nuclei are produced by collisions in the source itself[142] will not change any of the subsequent conclusions, since this assumption is merely equivalent to adding a certain thickness of matter traversed by the cosmic rays in the source itself. The only important fact is that the L nuclei are produced only by disintegration of heavier nuclei.

The results of the determination of the composition of the sources for different models are listed in Table VII. The composition of relativistic particles in the source is determined here for two sets of fragmentation probabilities p_{ik} (sets a and b of Table VI) and for three different models. This leads to the abundance of groups of nuclei VH, H, M, L, α, and p as observed on earth (see Column 6, Table I). The last line of Table VII gives for each model the values of the characteristic parameter, $\xi = 10^{-30}$ D/n, the traversed thickness of matter s, and the thickness of matter $\lambda_e = c\bar{\rho}T_e$ traversed prior to escaping from

*The small abundance of the L nuclei is due to their rapid "burn up" in nuclear reactions. Within the framework of the existing concepts concerning the formation of the elements, (see, for example, reference 141 and 116a), we cannot accept an assumption that the number of L nuclei in the sources is large.

TABLE VII. Composition of cosmic rays in the source

$\frac{q_i}{q_H}$	Equilibrium composition with allowance for escape [see (4.16), (4.20), and (4.27)]		Regular model [see (4.15) and (4.16)]		Diffusion model without allowance for reflection [see (4.16), (4.20), and (4.26)]		Average over the universe	
	a	b	a	b	a	b	see ref. 23	see ref. 24
1	2	3	4	5	6	7	8	9
q_{VH}/q_H	0.53	0.56	1	1	0.63	0.76	0.06	0.05
q_M/q_H	1.26	0.88	0.99	0.70	1.22	0.74	2.6	10.1
q_L/q_H	0.0	0.0	0.0	0.19	0	0	10^{-5}	10^{-5}
q_α/q_H	14	9.7	13.9	12.4	13.9	9.1	260	1040
q_p/q_H	131	101	169	179	125	97	3400	6800
	λ_e=17 g/cm²	λ_e=27 g/cm²	s=6.5 g/cm²	s=6.5 g/cm²	ξ=2.3	ξ=1.5		

the galaxy [see (4.27)]. All these values have been obtained from the condition that there are no L nuclei in the cosmic-ray sources.*

Before we proceed to discuss the results given in Table VII, let us note the following very important circumstance: the diffusion model, in the presence of a strong reflection from the boundaries of the galaxy [see, for example, (4.23) for $\beta \ll 1$], cannot yield the composition observed on earth no matter what the composition of the sources, provided the boundary is not far enough to make its influence insignificant.† The calculations were made for values of the galactic radius (i.e., the distance from the center to the reflecting boundary) R = 12 kiloparsec and R = 16 kiloparsec. It has been found that in all cases, for any choice of the parameter ξ, there should be many more nuclei of group L than observed (we find that $N_L > N_H$ and $N_L/N_M > 0.5$). The situation is the same, naturally, with the "equilibrium" composition, which, as we have seen, serves as the limiting case for diffusion with reflection when $R \ll \sqrt{DT_i}$ (see Sec. 4c). Thus, if we exclude the possibility of a substantial change in the assumed parameters p_{ik} and λ_i, and if $N_L \leq N_H$ on earth, it must be assumed that either the reflection from the boundaries is small, or the assumed diffusion model of the propagation of cosmic rays in the galaxy is incorrect.

We note that the reflection has a particularly significant effect on the chemical composition if it is assumed that the process is stationary. But if we forego the idea of a stationary process and assume, for example, that the cosmic rays have been produced during an earlier stage of the evolution of the galaxy and are retained in it[107] (there is no escape at all), then no difficulties arise with the composition. But in such a model, the cosmic rays should traverse within the lifetime of the galaxy (approximately 10^{10} years) a thickness of matter $\sim$ 6.5 g/cm² (see Columns 4 and 5, Table VII), corresponding to an average gas concentration in the galaxy $n \simeq 4 \times 10^{-4}$ cm^{-3}. As noted in Sec. 3, this value is too low.

It follows from Table VI that the "regular" model does not lead to a contradiction in the composition of the cosmic rays as far as groups H, M, and L are concerned. One could therefore give up the diffusion model in favor of a strictly regular motion of the particles along the force lines of the galactic magnetic field. If the number of force lines leaving the galaxy is small, then in such a model a small fraction of the cosmic rays escapes the galaxy, which to some extent is equivalent to the presence of a reflecting boundary. With this model, however, it is difficult to explain the isotropy, for in the case of regular motion the particles propagate from the source along each force line in only one direction. Even if it assumed that the cosmic-ray fluxes along a given force line are the same in both directions (this needs special reasoning), an anisotropy in the composition of the cosmic rays should be observed in this case, too, since the traversed thickness of matter depends essentially on the angle between the velocity of the particle and the direction of the magnetic field (we speak of spiral motion of cosmic rays along the magnetic force lines).

As regards the equilibrium composition with allowance for the escape of particles [see (4.27)], here, too, the observed composition can be explained only by assuming considerable leakage of particles from the galaxy: it is assumed in Table VII that $\lambda_e \simeq$ 17 to 27 g/cm², whereas the absorption range of protons is λ_p = 72 g/cm² (i.e., $\lambda = c\bar{\rho}T$ = 14 to 20 g/cm², where T is a total lifetime of the proton in the galaxy, $T^{-1} = T_p^{-1} + T_e^{-1}$).

Thus, although it is not yet proved that a change of model will not explain the chemical composition of the

*An exception is the regular model with set b of the parameters p_{ik}. In this case the problem has no solution when $q_L/q_H = 0$, and Table VII indicates the minimum possible value, $q_L/q_H = 0.19$.

†The difficulties that arise in connection with the chemical composition of the cosmic rays with allowance for reflection were first indicated by Davis.[108] He noted especially that in the presence of reflection too many protons and α particles are produced. This complication can be circumvented by assuming that the protons and α particles are almost not accelerated in the sources. We arrive, however, at the even more radical conclusion, that it is impossible to reconcile the data even for nuclear groups H, M, and L.

cosmic rays even in the presence of total reflection from the boundary of the galaxy, it appears to us, nevertheless, more natural to conclude that the reflection is insignificant and at the same time to retain the diffusion model. The assumed escape of cosmic rays from the galaxy may not even contradict here the model of the "force-line cage," if we speak of escape as a result of instability and the associated "ejection" of cosmic rays out of the galaxy (see reference 101 and 3c).

It follows from the statements made in Sec. 3c and from the estimate which will be given below that from the energy point of view this calls for an increase of source power by only one order of magnitude.

The second important conclusion which can be made in an analysis of the results given in Table VII, is that the cosmic rays in the sources should contain a very considerable amount of very heavy nuclei. The fraction of these can be estimated from the relations $N_{VH} = q_{VH}F_{VH}$ and $N_H = q_HF_H$ [see (4.16) and (4.20) with $i = 1$] and from the known ratio $N_{VH}/N_H = 0.28$ near the earth. We see that in all the models considered the group of H nuclei in the source consists of a considerable fraction of VH nuclei. Furthermore, if $N_{VH}/N_\alpha = 2 \times 10^{-4}$ to 5×10^{-5} in nature, then $N_{VH}/N_\alpha = 0.1$ to 0.05 in the sources of cosmic rays, i.e., there are approximately one thousand times more heavy nuclei for the same amount of α particles than in the universe on the average.

We have used the ratios of the concentration of VH nuclei to the concentration of α particles, instead of the customary ratios of the concentration of H nuclei or VH nuclei to the proton concentration, since an estimate of the number of protons in the source calls for knowledge of the probabilities p_{ip}, about which little is known at present. The values of q_p listed in the table have been estimated from the total flux of nucleons observed near the earth, under the assumption that the average absorption range for nucleons is $\lambda_{nucl} \simeq \lambda_p = 72$ g/cm^2. Then

$$\frac{N_{nucl}}{N_H} = \frac{q_{nucl}}{q_H}\frac{F_{nucl}}{F_H} \text{ and } q_p = q_{nucl} - \sum_{i=H,\,M,\,L,\,\alpha} A_i q_i. \quad (4.29)$$

These singularities in the composition of relativistic particles in the source can hardly be attributed merely to an anomalous composition of elements in the source, without making use of the mechanism of preferred acceleration of heavy elements. In fact, the observations do not lead as yet to so large a content of very heavy nuclei, compared with the average and with the content of α particles in the atmospheres of stars and in gas nebulae, i.e., in the regions where cosmic rays originate. Within the framework of the theory of the origin of the elements, a considerable excess of heavy nuclei can, to be sure, be obtained in the internal parts of the stars, but whether it can be retained when the gas leaves through the surface of the star is a moot question. True, it is frequently assumed that supernovae, in particular, are anomalously rich in heavy elements, but this does not imply several orders of magnitude. Finally, even assuming that the cosmic-ray sources are considerably richer in heavier elements then the known astronomical objects, it would still be necessary to show, from this point of view, that the particles retain the same composition after injection and acceleration from thermal to relativistic energies, which in itself is far from obvious.

On the other hand, the possibility of preferred acceleration of the heavy nuclei, indicated in Sec. 4b, does not stipulate a specific source composition, and yields a natural explanation for the excess of heavy nuclei among the accelerated particles.

In this connection we note that it is possible to obtain a composition of cosmic rays close to that observed on earth by assuming that only the VH nuclei are accelerated in the sources.[136*] The results of the calculation of the composition are given for this case in Table VIII. Here, in view of the absence of data on the probabilities of fragmentation for the VH group in hydrogen, the fraction of VH nuclei on earth is estimated from the relation $N_{VH}/N_H = F_{VH}/F_H$ [this relation is obtained under the assumption that the H group from the source consists wholly of VH nuclei and consequently, $q_H = q_{VH}$; see (4.20)]. The number of protons relative to VH nuclei has been estimated from (4.29), where it is assumed that the intensity of the source, as regards nucleons, is $q_{nucl} = \bar{A}_{VH}q_{VH}$, where $\bar{A}_{VH} = 50$ is the average atomic weight of the VH group. The last row of the table gives the assumed optimum values of the characteristic parameters for different models. We note that as the thickness of matter traversed is increased (large values of s, or correspondingly, smaller values of ξ), all the ratios except N_{VH}/N_H increase, and N_L/N_H becomes substantially greater than that observed. To the contrary, as the thickness of the traversed matter is decreased (smaller s or, correspondingly, larger ξ), the ratio N_L/N_H decreases, but on the other hand the ratios N_M/N_H, N_α/N_H and N_pN_H become too small. As can be seen from the table, a composition closest to that observed is obtained with the diffusion model without reflection, for $\xi = 0.6$ and set b of the fragmentation probabilities. At the same time, the value $\xi = 10^{-30}$ D/n ~ 0.6 is too small, for even when $n \sim 0.1$ we obtain $D = lv/3 \sim 3 \times 10^9 l \sim 6 \times 10^{28}$, or a mean free path $l \sim 6$ parsec.

Incidentally, the question of the value of l must still be considered moot. One customarily uses large values, $l \sim 100$ parsec, but it is possible that these values pertain to large inhomogeneities, while it is the smaller inhomogeneities which are of importance in the scattering of cosmic rays (see Sec. 2b in this connection).

*The possibility that the observed composition is the result of fragmentation of heavy nuclei was considered also in reference 26.

TABLE VIII. Composition of cosmic rays if only VH nuclei are accelerated ($\bar{A} = 50$)

N_i/N_H	Equilibrium composition [see (4.27a)]		Regular model [see 4.15)]		Diffusion model without reflection [see (4.26)]		Diffusion model with total reflection [see (4.25)]		Composition of cosmic rays observed on earth	
	a	b	a	b	a	b	a	b	average	limits (tentative)
N_{VH}/N_H	0.45	0.45	0.1	0.12	0.18	0.21	0.27	0.27	0.28	0.20—0.30
N_M/N_H	0.93	1.33	1.82	2.2	1.68	2.14	1.26	1.8	2.2	2.0 —2.5
N_L/N_H	0.63	0.66	1.0	0.66	1.15	0.99	1.04	1.15	0.8	0.5 —1.0
N_α/N_H	10.3	18.3	11.8	16.1	17.6	24.6	15.8	27.0	35	30—40
N_p/N_H	510	472	200	116	471	320	755	702	520	500—600
			$s=12$ g/cm^2	$s=10.6$ g/cm^2	$\xi=0.5$	$\xi=0.6$	$\xi=1$	$\xi=1$		

It must be borne in mind that the assumed acceleration of heavy nuclei only is an idealization. Actually, there will exist a certain finite, although relatively small flux of other nuclei from the region of thermal into the region of relativistic energies. What is important here is that the injection conditions are most favorable for the heavy nuclei, and therefore their percentage in the total number of accelerated particles is considerably increased above the initial value.

Let us dwell in somewhat greater detail on the diffusion model without reflection. In the diffusion model it is easy to calculate the degree of cosmic-ray anisotropy, δ, using the formula (see reference 1)

$$\delta = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} = \frac{4D}{c} \frac{1}{N} \left| \frac{dN}{dr} \right|. \qquad (4.30)$$

Assuming $D = 10^{29}$, we obtain from (4.30) and (4.26) $\delta_a = 1.4 \times 10^{-3}$ and $\delta_b = 1.6 \times 10^{-3}$ for H nuclei (the indices a and b indicate variants a and b in Table VII). For the total nucleon flux, $\delta_a = 7.9 \times 10^{-4}$ and $\delta_b = 8.5 \times 10^{-4}$. The value $D = 10^{29}$ is chosen in accordance with the data on the chemical composition, and corresponds to a "range" $l \simeq 10$ parsec (it is hardly possible to put $D \simeq 10^{30}$ here, since $D/n = 10^{30}\xi \sim 10^{30}$ from data on the chemical composition, and there is no justification for putting $n > 0.1$ even in the galactic plane).

Let us estimate, finally, the cosmic-ray source power necessary for the diffusion model without reflection, (4.26). According to reference 143, the flux of primary cosmic rays near the earth amounts to 0.18 particle/cm^2 sr-sec. Consequently, considering in accordance with Table I the contribution of nuclei with $A > 1$ we obtain a total nucleon flux $I_{nucl} = 0.24$ nucleon/cm^2 sec-sr and a concentration $N_{nucl} = 4\pi I_{nucl}/c = 1.0 \times 10^{-10}$ nucleon/cm^3. Then from (4.26), with $\lambda_{nucl} = \lambda_p = \bar{\rho} c T_p = 72$ g/cm^2, $r = 8$ kiloparsec $= 2.5 \times 10^{22}$ cm, $D = 10^{29}$ cm^2/sec, and $\xi = 1.5$ to 2.3 (see Table VII), we obtain for the intensity of the sources

$$q_{nucl} \simeq (5-6) \cdot 10^{42} \text{ nucleons/sec.} \qquad (4.31)$$

At an average cosmic-ray energy $\bar{\epsilon} \simeq 5$ Bev/nucleon, the theoretical source power should be accordingly

$$U = q_{nucl}\bar{\varepsilon} \simeq 3 \cdot 10^{52} \text{ ev/sec} \simeq 5 \cdot 10^{40} \text{ erg/sec.} \qquad (4.32)$$

This value of source power is one order of magnitude greater than the estimate obtained in Sec. 3 [see (3.3)]. However, as was already noted in Sec. 4a, new data allow us to raise the estimated energy rating of the sources. We note that, on using the relation $U = W/T$, the value given in (4.32) leads [see (3.3)] to a time $T \sim 3 \times 10^7$ to 3×10^8 years if $W \sim 10^{56}$ to 10^{57}. Obviously, the time is here $T \ll T_p \sim 3 \times 10^9$ years and consequently it is equal in practice to the time of diffusion escape of the cosmic rays from a galaxy of radius $R \sim (3 \text{ to } 5) \times 10^{22}$ cm.

In the presence of reflection, the values of the coefficient δ and of the power U can only be smaller than in the case of an open model. Thus, the only evidence in favor of absence of reflection from galactic "boundaries" are the data on the chemical composition of the cosmic rays. As is clear from the foregoing, the corresponding conclusions are thus far tentative — they have been obtained under the assumption that the diffusion approximation is correct and by using various parameters whose values have not yet been finally established.

CONCLUDING REMARKS

The status of the theory of the origin of cosmic rays is sometimes viewed rather pessimistically, because it is frequently necessary to use in this field rough approximate values instead of exact calculations, and in some cases the answers to important questions are not unequivocal. It goes without saying that different opinions can be entertained at the present state of the problem, and no unity can be expected in the views on the origin of cosmic rays. At the same time, we wish to emphasize that some of the critical remarks made in this respect are nevertheless the result of misunderstandings due to a "physical" approach to astrophysics. The origin of cosmic rays is actually an astrophysical problem, and this is naturally not altered by the fact that it is mostly physicists who are interested in it. On the other hand, we cannot apply to astrophysics (or, for example, biophysics and even geophysics) criteria that are suitable for different branches of modern physics. To forget this is to assume a position analogous to that of those mathematicians who believe that even the better theoretical formulations of the physicists are insufficiently rigorous or not proved. We know that theoretical physics, is advancing rapidly in spite of a "lack of mathematical rigor." Recent progress in astrophysics is equally astonishing, even if we do not refer to precise measurements. For example, the determination of the magnitude of interstellar magnetic field, with an intensity on the order of $10^{-6} - 10^{-5}$ oe, accurate to a factor on the order of unity, must be acknowledged to be an outstanding accomplishment. It is enough to consider the complexity of this problem, which appeared utterly insoluble only relatively recently. Analogously, only a few years ago all hypotheses concerning the origin of cosmic rays were almost purely speculative and there was no real hope of investigating cosmic rays beyond the limits of the solar system. Now, however, with the development of radio astronomy, we can determine the character of the energy spectrum of relativistic electrons in different regions of the galaxy and far beyond its limits.

It is likewise impossible to lose sight of these cardinal shifts and to attempt even now to judge all the problems in the theory of the origin of cosmic rays at the level of the theory of cyclic accelerators or cascade showers.

Progress in the theory of the origin of cosmic rays was attained via an extensive utilization of astrophysical (in particular, radio-astronomic) data in conjunction with a study of primary cosmic rays near the earth and an analysis of certain theoretical problems. Further progress can be expected only through an all-out utilization of different possibilities and through many more experiments.

Radio-astronomical methods can be used to obtain better data on radio emission (the intensity, spectrum, and, sometimes polarization) in the halo, disk, spiral, and the center of the galaxy, as well as data on radiation from galactic nebulae (primarily, shells of supernovae). The possible radio emission from novae and a few other nonstationary stars is of interest. A study of different galaxies, especially those related to ours (M31 in Andromeda and others), made at several frequencies with the aid of large radio telescopes, will probably yield information on the character of the galactic boundaries, on the relativistic electrons, on the magnetic fields between galaxies, etc. The origin of radiating electrons in the halo will perhaps be explained through a detailed determination of the spectrum of the radio emission as a function of the galactic coordinates (see Sec. 3e).

Observation of the lines of neutral hydrogen ($\lambda = 21$ cm) will apparently yield more exact data on the density of the gas in the galactic halo. The density can also be estimated, in principle, by determining the spectrum of the long-wave cosmic radio emission (see Sec. 3a).

Directly related to the origin of cosmic rays are also numerous astrophysical investigations of the structure of the galaxies, the galactic magnetic fields, the interstellar and intergalactic medium, and the nonstationary stars (particularly supernovae), etc.

Special mention must be made of the theoretical problems connected with clarification of the features of motion of cosmic rays in a magnetic field (accuracy of the diffusion approximation, role and mechanism of violations of the adiabatic invariant, etc), with the mechanism of the bursting and scattering of shells of supernovae, and with the acceleration of cosmic rays in these shells.

An entire series of important points must also be clarified by further investigation of the primary cosmic rays near the earth. Thus, a more exact determination of the charge spectrum of primary cosmic rays will make it possible to ascertain whether the particles accelerated in the sources are predominantly the heavy nuclei or all the nuclei (the presence of a deep gap in the charge spectrum will be evidence in favor of the second possibility; see Sec. 1a). This includes also the final resolution of the long-standing discussion concerning the number of Li, Be, and B nuclei in the primary cosmic rays, and a determination of the number of He^3, H^2 (deuterium), and many other isotopes.

In addition to a direct determination of the chemical composition of the cosmic rays, a determination of their composition in the sources calls for knowledge of the probability of transformation and fragmentation of different nuclei as they move in the interstellar medium (hydrogen, helium). To obtain these probabilities, we cannot use merely the data obtained with photographic plates but, apparently, the more reliable radiochemical methods, associated with the use of accelerators or with the observation of the fragments produced from cosmic rays passing through a layer of balloon-borne liquid hydrogen.

Another most important problem is the determination of the chemical composition of cosmic rays at high energies. We have seen in Secs. 3 and 4 that heavy nuclei, with energy $\lesssim 10^{19}$ ev, can still be of galactic origin, whereas protons of the same energy should in all probability come from the metagalaxy. Closely connected with this problem is the question of the variation of the energy spectrum at high energies and of the possible connection between these variations and the variability of the chemical composition of the cosmic rays, or the increased role of cosmic rays of metagalactic origin. A study of cosmic rays of high and ultrahigh energy is essential also from the point of view of determining the degree of anisotropy δ (see Sec. 1b).

Another urgent problem is the determination of the number of primary electrons and, separately, positrons (with energy $E \gtrsim 10^9$ ev) near the earth; let us recall also the existence of primary γ rays.* The latter should be emitted from cosmic-ray sources such as supernovae or bright "radio galaxies" (A Cygni, A Virginis).

We know that a study of cosmic rays of solar origin and of the variation of the cosmic-ray intensity is becoming an ever more effective method of investigating interplanetary magnetic fields and processes on the sun. At the same time, the mechanism of acceleration of cosmic rays on the sun is of interest also from the point of view of the theory of origin of cosmic rays (it is particularly important to determine the charge spectrum of cosmic rays of solar origin). Closely related to the problem of the variations is the "high-latitude cutoff" of the cosmic-ray spectrum. Is this cutoff magnetic and does it originate within the solar system, or does it reflect in some manner the character of the acceleration of cosmic rays in the sources? This important question has not yet been finally answered, although the most widely held opinion is that the cutoff is due to the influence of the ordered magnetic field of the solar system or to random fields in the interplanetary medium, but not to the effect of sources or to the slowing down of the cosmic rays in interstellar space.

We can thus indicate a whole series of specific experiments and observational methods, the use of which will answer many of the moot questions. True, some experiments call for great efforts (for example, the observation of electrons and positrons in primary cosmic rays is quite complicated even if satellites are used, since the flux of the light particles should amount to only a fraction of a percent of the total flux of the cosmic rays). On the other hand, solutions of individual problems can be expected within the nearest future. This applies, for example, to the final establishment of the amount of primary Li, Be, and B nuclei and the clarification of the question of the gaps in the charge spectrum of the cosmic rays. There are therefore grounds for hoping that at the next International Conference of Cosmic-Ray Physics (Japan, 1961) noticeable progress will be noted also with respect to the origin of cosmic rays.

NOTES ADDED IN PROOF

I. A direct experiment capable of explaining the nature of the high-latitude cutoff consists of measuring the flux of cosmic rays as a function of the distance from the sun (if the flux is constant, the cutoff obviously occurs outside the solar system). The successful launching of space rockets makes such an experiment fully feasible.

II. If the high-latitude cutoff is connected with the spectrum of the sources, this cutoff may not occur for electrons and positrons: the secondary electrons and positrons which, probably, play an important role (see Sec. 3e) outside the solar system, should also have energies below the limit of the high-latitude cutoff. There are no experimental data concerning electrons and positróns on earth with energies less than $\sim 10^9$ ev (see references 1 and 48; naturally, we do not mean here the electrons in the radiation belts).

III. In an interesting paper[144] published after the present article went to press, a model is also proposed, in which the magnetic field in the spiral, and in particular in the halo, is random to a considerable extent, and the field in the halo consists so to speak of individual loops (rings of force lines). Such "loops" represent a certain modification of magnetic "clouds" or inhomogeneities that scatter cosmic rays. The existence of these clouds is assumed in the diffusion model. In this connection, the diffusion approximation in the model of reference 144 should be sufficiently good, and no galactic boundaries exist (in other words, the reflection from the "boundaries" of the halo can be considered nonexistent, and some arguments in favor of this are given in the present article; see Sec. 4d).

*We recall that primary electrons and positrons, let alone γ rays, have not been experimentally observed as yet (see Sec. 1b).

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