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ORIGIN OF COSMIC RAYS*

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THE present paper describes the status of the problem of origin of cosmic rays (or, using a more modern and more accurate title, the status of the astrophysics of cosmic rays), with inclusion of the new work reported after the conference in India (Jaipur, 1963). As in the paper presented to the Indian conference[1], we do not attempt here a most extensive and detailed coverage of the material (see [2]), but discuss only several individual problems.

1. SOLVED AND UNSOLVED PROBLEMS OF COSMIC-RAY ASTROPHYSICS

The vigorous development and undisputed success attained in the last 10—15 years in the field of the astrophysics of cosmic rays should, of course, not obscure the fact that there are many essential points in this field which still remain unclear.

We therefore begin with a brief discussion of the present status of the following question: What is clear and what is unclear in the astrophysics of cosmic rays?

There is no longer any doubt that cosmic rays, together with stars and interstellar gas, are among the main elements constituting the galaxies and the universe as a whole. This conclusion is connected not only, and even not so much, with the circumstance that the cosmic rays are observed in a great variety of objects (galaxies, radiogalaxies, quasars, supernova shells, the Sun), as with the relatively large energy density and pressure of the cosmic rays. Thus, for example, even in our Galaxy, which is "normal" in the radio band, the energy density of the cosmic rays is $w_G \sim 10^{-12}$ erg-cm^{-3}. At the same time, the intensity of the galactic magnetic field is $H_G \sim 3-10 \times 10^{-6}$ Oe and is such that $H_G^2/8\pi \sim w_G$; of equal order of magnitude is the density of the internal energy $\epsilon \sim nkT$ of a gas with concentration $n \sim 1$ and temperature $T \sim 10^4$ °K, and, consequently, in most regions of the Galaxy we have $\epsilon \lesssim w_G$. In radiogalaxies we encounter cosmic-ray energy densities which sometimes are even several orders of magnitude higher than w_G. One can hardly doubt that the energy and the pressure of the cosmic rays play an essential, and in some cases probably a decisive role, in the understanding of dynamics of galactic halos, supernova shells, radio-emitting clouds and radiogalaxies (for example, in A-Cygni), continuous-emission jets in radiogalaxies and quasars (A-Virginis ≡ NGC 4486, 3C 273-B and others), etc.

Another point which must be emphasized is the universal character of effective acceleration of cosmic rays. This means that the acceleration of cosmic rays (i.e., generation of relativistic particles) is not an exclusive effect that takes place under special conditions, but is observed as a rule: the particles are effectively accelerated on the Sun, in the Earth's radiation belt, and in stellar explosions and in radiogalaxies. This result is in general perfectly understandable within the framework of existing concepts of plasma physics and magnetohydrodynamics. Indeed, plasma states wherein the plasma contains different moving regions (beams and jets, waves, etc.), but has no magnetic field or fast particles, are in general unstable. Therefore even if some explosion (for example, a supernova explosion) could be considered during its early stage without taking into account the influence of the field and the cosmic rays, both a field and cosmic rays would appear after a certain time. The question of the level to which the field energy and the cosmic-ray energy can rise cannot have a universal solution—the answer depends on the time of development of the process and other factors. In many cases, however, we can expect the establishment of a certain quasi-equilibrium, at which the energy densities of different types are of the same order of magnitude, that is,

$$w_{\text{c.r.}} \sim \frac{H^2}{8\pi} \sim \frac{\rho u^2}{2}, \tag{1}$$

where ρ is the gas density and u its characteristic velocity.

In addition to the indicated general conclusions, there are many radioastronomical data concerning the spectrum of the electronic component of the cosmic rays in different regions and objects[2,3], and also information on the cosmic rays on Earth[2,4]. We confine ourselves here only to several brief conclusions.

The chemical composition of cosmic rays on Earth offers evidence that the relativistic nuclei contained in them have traversed a distance 2—10 g/cm^2; at an average interstellar-gas density (in the region occupied by the cosmic rays) $\rho \sim 10^{-26}$ g/cm^3 this corresponds to a path $L \sim 5 \times 10^{26}$ cm and a time $T \sim 10^{16}$ sec $\sim 3 \times 10^8$ years. Either the sources of the galactic cosmic rays should be anomalously rich in nuclei of

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the M and H groups, or, which is more probable, the acceleration of such nuclei should be more effective than the acceleration of protons and α particles.

Information of the electron-positron components[2,4] is still very incomplete. As a crude approximation, however, they are, on the one hand, in agreement with the radioastronomical data, and on the other hand they confirm the conclusion that most cosmic-ray electrons on Earth are of primary origin (i.e., these electrons are not the product of $\pi \rightarrow \mu \rightarrow e$ decay)[1,2,5] (see the Appendix).

The aggregate of all the available data is in our opinion fully compatible with the galactic theory of the origin of cosmic rays observed on Earth; exceptions are particles with $E \gtrsim 10^{16}$–10^{17} eV, which are more likely to enter the Galaxy from the outside and to be generated, for example, in radiogalaxies (in what follows, however, we have in mind only the main part of the cosmic rays, corresponding to energies $E \lesssim 10^{13}$–10^{15} eV). The main sources of cosmic rays in the Galaxy are then supernova stars and possibly explosions of the galactic core. These sources should ensure injection of cosmic rays in the interstellar space with a power (for details see [1,2])*

$$U_{\text{c.r.}} \sim 10^{40} - 10^{41} \text{ erg/sec},$$
$$U_e \sim 3\cdot 10^{38} - 3\cdot 10^{39} \text{ erg/sec}. \qquad (2)$$

Here $U_{\text{c.r}}$ pertains to all the cosmic rays and U_e to their electronic component.

The powers in (2) are very high (for example, the value $U_{\text{c.r}} \sim 3 \times 10^{40}$ is obtained if supernova explosions occur in the Galaxy on the average once every 100 years, and the explosion energy going over into cosmic rays is on the average 10^{50} erg), but are still admissible with respect to the indicated sources (see Sec. 4). At the same time, there are no independent data to confirm that such an injection is indeed realized by the galactic sources. Therefore the main question in the theory of the origin of cosmic rays in the Galaxy still remains unsolved, namely, the question of the possible role of the influx of cosmic rays of metagalactic origin into the Galaxy. Section 2 of this paper is devoted to this problem and to metagalactic cosmic rays in general. We list here a few other unclear or insufficiently clear matters.

1. The energy spectrum of the cosmic rays observed on Earth** has in the low-energy region a maximum which is observed even during the time of the solar minimum[4,6]. This raises the important question of whether a maximum exists also in the spectrum for interstellar space, or whether it is due entirely to the influence of the interplanetary medium (the effect of inhomogeneities in the solar wind, etc.). The latter conclusion was arrived at in [6], but it is then necessary to explain why the cosmic rays far from the solar system do not have a spectral maximum in the energy region under consideration, $E_c \gtrsim 10^8$ eV/nucleon, in spite of the increase of the ionization losses on going over to nonrelativistic energies. Of course, the question of the position of the maximum in the spectrum is quantitative, and even the absence of this maximum at $E_c > 10^8$ eV/nucleon will not contradict anything until a detailed analysis is made. But it is precisely the need for verifying the spectrum in the low-energy region which we wish to emphasize.

2. Anisotropy of cosmic rays has apparently never been observed in any energy region. Even if an anisotropy is observed in years of the solar minimum[2,4] for the main part of the cosmic rays, it does not exceed in any case fractions of 1%. The practically complete isotropy of the cosmic rays is in agreement with the galactic theory in which the diffusion approximation is used.[2] On the other hand, the very character of the diffusion (propagation) of the cosmic rays in the Galaxy and in magnetic fields in general is not sufficiently clear as yet. It is therefore perfectly possible that the isotropy of the cosmic rays reflects directly the specific nature of the motion of cosmic rays in the interstellar plasma. We shall show below that there are several grounds for such a point of view.

3. Speaking of unclear items, we cannot fail to point to the lack of information on cosmic rays of superhigh energy ($E > 10^{15}$ eV; we are referring to the energy spectrum and the chemical composition), the spectrum of the electron-positron component on Earth and the percentage of the positrons in this component, and also the lack of data on cosmic γ rays (all we know here is the upper limit of the flux[1,2,7]). The vital problems in the field of the study of chemical composition of cosmic rays are presently known and consist of determining the isotopic composition (for example, the fraction of D and He^3 in hydrogen and helium), clarification of the dependence of the composition on the energy (at low energies it is necessary to know above all the ratio $L/(M+H)$; see [4,8,9] and below), etc. When the information on the chemical composition and on the fragmentation parameters of the colliding nuclei becomes sufficiently precise, very interesting opportunities will arise with respect to the choice and refinement of different models proposed to describe the motion of cosmic rays in the Galaxy; (see [2], Sec. 15, and Sec. 4).

4. From the theoretical point of view, in addition to the questions considered above, there are also several other unanswered questions. What is the concrete mechanism of acceleration of cosmic rays in different cases (supernova explosions, processes in galactic

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*We have reduced by several times the lower limit for $U_{\text{c.r}}$ and U_e in comparison with[1,2,5]. The value $U_{\text{c.r}} \sim 10^{40}$ erg/sec corresponds to the total energy of the cosmic rays in the Galaxy $W_{\text{c.r}} \sim 10^{56}$ erg and to a time of emergence of these rays from the system $T_{\text{em}} \sim 3 \times 10^8$ years $\cong 10^{16}$ sec. Such an estimate seems to us perfectly acceptable (see secs. 3 and 4).

**Cosmic rays of solar origin are not considered in the present article.

cores, acceleration at the Sun and in stellar atmospheres)? Essentially, we know very little here and it is necessary to explain both the high acceleration efficiency and the dependence of this efficiency on the charge and mass of the particle (we refer in particular to the acceleration of electrons). We can include here also the known fact that the acceleration energy spectrum is universal, although something has already been done in this respect (see [10] and [2], Secs. 9 and 15, and also Sec. 4).

It is known from observations that the cosmic rays remain in supernova shells a rather long time; at the same time the magnetic field in the central part of the shells (we refer concretely to the Crab nebula) is either highly ordered or, at any rate, has a large ordered component. In an ordered field, the cosmic rays would pass through the Crab nebula, whose diameter of the order of 1 psec, within only a few years, whereas the age of this shell exceeds 900 years. A similar problem arises with respect to the radioemitting clouds and regions in radiogalaxies and normal galaxies. It is simplest to explain the retention of cosmic rays in shells or radioemitting clouds, by assuming their boundaries to have strongly turbulized regions through which the cosmic rays diffuse only slowly (an alternative possibility is to admit that besides the ordered component of the field in the shells and in the clouds there is a large unordered component of the field, and by the same token, that the motion of the cosmic rays is very strongly hindered in the entire shell). But in this case it is necessary to explain why such a turbulized shell is produced.

There are indications and arguments (in particular, this is the case if the x-ray emission from the Crab nebula is of the synchrotron radiation type; see [11]), favoring a continuing acceleration of the cosmic rays in the Crab nebula and other objects, for example in the exploding Galaxy M 82 (see [12]). But what is the source and mechanism of the acceleration after the explosion of the supernova or the galactic nucleus? This is a still unanswered question. The same can be said concerning the very nature of the radiogalaxies and quasars, which we cannot stop to discuss in detail[13-13b].

Thus, there is indeed an appreciable number of unsolved problems. In Sec. 3 below we shall attempt to show that we can hope to solve some of these problems by including plasma phenomena. Many problems (including the question of nonstationary models of the origin of galactic cosmic rays, which we did not yet mention) will be discussed also in Sec. 4. Now we shall stop to discuss the problem of metagalactic cosmic rays and the origin of cosmic rays observed on Earth.

2. METAGALACTIC COSMIC RAYS AND ORIGIN OF COSMIC RAYS OBSERVED ON EARTH

We consider it highly probable that the energy density w_{MG} of cosmic rays in the metagalaxy (that is, averaged over metagalactic space) is several orders of magnitude lower than the galactic density:

$$w_{MG} \ll w_G \sim 10^{12}\ \mathrm{erg/cm^3}. \tag{3}$$

Specifically, it is most probable that $w_{MG} \lesssim 10^{-15}$ erg/cm^3. Let us list briefly (for more details see [1,2]) the arguments in favor of the correctness of inequality (3).

1. The kinetic-energy density of the intergalactic gas is

$$K = \frac{\varrho u^2}{2} \leqslant 10^{-14} - 10^{-15}\ \mathrm{erg/cm^3}\ (\varrho \leqslant 10^{-29}\ \mathrm{g/cm^3},$$

$$u \sim (1 - 5)\cdot 10^7\ \mathrm{cm/sec}),$$

and the energy density of the metagalactic magnetic field is $H_{MG}^2/8\pi \lesssim 10^{-15}$ erg/cm^3 ($H_{MG} \lesssim 10^{-7}$ Oe; see [1,2,14]), even more probably $H_{MG}^2/8\pi \lesssim 10^{-16}$–$10^{-17}$. At the same time, it is quite difficult and unnatural to assume that the energy density of the cosmic rays w_{MG} greatly exceeds $\rho u^2/2$ or $H_{MG}^2/8\pi$. From this we arrive at the estimate $w_{MG} \lesssim 10^{-15}$ erg/cm$^3 \ll w_G$.

2. We can estimate the density of the cosmic rays w_{MG} which enter the metagalactic space from the normal galaxies and the radiogalaxies. Thus we arrive at the estimate $w_{MG} \sim 10^{-16}$–10^{-17} erg/cm^3, and at any rate we see no possibility of obtaining values of w_{MG} comparable with w_G without strongly stretching a point.

3. From radioastronomical data (we refer to the lack of noticeable radioemission from the metagalactic space) we can draw definite conclusions concerning the metagalactic field H_{MG} and the energy density of the electronic component of the metagalactic cosmic rays $w_{e,MG}$. Thus, for $H_{MG} \sim 3 \times 10^{-8}$ we have $w_{e,MG} \lesssim 10^{-2} w_{e,G} \lesssim 3 \times 10^{-16}$ ($w_{e,G} \lesssim 3 \times 10^{-14}$—energy density of the electronic component in the Galaxy). Further, there are no grounds for assuming that the ratio $\frac{w_{e,MG}}{w_{MG}} < \frac{w_{e,G}}{w_G} \sim 10^{-2}$. From this we get $w_{MG} \lesssim 10^{-14} \ll w_G$.

4. The established upper limit of the flux of cosmic γ rays[7] also allows us to estimate the highest value of $w_{e,MG}$. Even if we assume that the energy density of the optical radiation in the Metagalaxy is $w_{ph} = 2 \times 10^{-3}$ eV/cm^3, we get $w_{e,MG} \leq 1$–$3 \times 10^{-2} w_{e,G}$. It is more probable that $w_{ph} \cong 5 \times 10^{-3}$–$10^{-2}$ (see [15,58])* and thus $w_{e,MG} \lesssim 10^{-2} w_{e,G}$. From this we arrive at

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*We do not exclude the possible existence of sufficiently powerful metagalactic radioemission at centimeter and shorter wavelengths[47]. At 7.3 cm, the radiation temperature is T = 3.5 °K, which for a black body corresponds to an energy density $w_{ph} \approx 0.7$ eV/cm^3. In this case the metagalactic electrons with energy, say, $E = 10^9$ eV lose one-half their energy, as a result of Compton losses, within a time $T = 5 \times 10^8$ years. The scattering of radio-photons with average energy $\epsilon \approx 2.7\,kT = 0.8 \times 10^{-3}$ eV by relativistic electrons leads to the emission of x rays. Using the observed data on the x-ray background[11], we can conclude that $w_{e,MG} < 10^{-5}$ eV/cm$^3 \cong 3 \times 10^{-4}\ w_{e,G}$.

the same estimate for w_{MG} as in the preceding item 3. It is more important, however, that even the inequality that follows directly from the observations,

$$w_{e,\mathrm{MG}} \ll w_{e,\mathrm{G}} \qquad (3a)$$

already contradicts the metagalactic theory of the origin of cosmic rays observed on Earth. In fact, the electronic component of the cosmic rays in the Galaxy is primary[1,2,5], that is, it is not produced by the nucleonic component. Therefore the observed electronic component would have a metagalactic origin only if $w_{e,MG} \sim w_{e,G}$ (the additional assumption needed here, namely, that the metagalactic cosmic rays are isotropic, is discussed later).

5. From data on the background of the cosmic x-rays[11] we can conclude, subject to several additional assumptions (see Sec. 3) that $w_{MG} \lesssim 10^{-2} w_G$.

6. The value $w_{MG} \sim 10^{-17}$–10^{-15} erg/cm^3 is likewise far from small when we compare the energy of metagalactic cosmic rays not only with $\rho u^2/2$ and $H^2/8\pi$ in the intergalactic medium, but also with the kinetic energy of the random motion of all the galaxies.

7. Not only are there no data whatever favoring the violation of the inequality (3) on the assumption that $w_{MG} \sim w_G$, but in effect there are no arguments whatever other than the possibility of assuming in this case that cosmic rays in the galaxy and in other normal galaxies have a metagalactic origin. Yet a similar metagalactic theory encounters, in addition to all other difficulties, also certain difficulties when it comes to explaining the chemical composition of the cosmic rays (metagalactic cosmic rays produced during the pregalactic stage of evolution of the metagalaxy would be probably poor in heavy elements; on the other hand, as indicated in item 2, there are in all probability not enough galactic cosmic rays for the accumulation of cosmic rays with energy density $w_{MG} \sim w_G$).

Thus, let us assume that inequality (3) holds (especially near our Galaxy), and that in this case the cosmic rays in the metagalactic space are isotropic. Then it is perfectly probable that an appreciable part of the cosmic rays observed on Earth (and in the Galaxy in general) have a metagalactic origin. In fact, if the influx of cosmic rays into our Galaxy is approximately stationary, then by virtue of the Liouville theorem the intensity of the cosmic rays is constant along the particle trajectories. If the cosmic rays are isotropic in the Metagalaxy and in the Galaxy, it follows therefore* that the energy of the metagalactic cosmic rays in the Galaxy is $w_{MG,G} = w_{MG}$. We can readily arrive at the same conclusion from a more detailed analysis of the motion of the particles as they go over from the metagalaxy (field H_{MG}) into a region with galactic field $H_G \gg H_{MG}$. Due allowance for the nonstationary behavior with which the violation of the Liouville theorem may be connected could somehow disturb the equality $w_{MG,G} = w_{MG}$. However, under the concrete conditions of our Galaxy (and of all galaxies in general), we see no way whatever or any conceivable mechanism to "pump" cosmic rays from metagalactic space into the Galaxy. Therefore, if Eq. (3) is satisfied, the only possibility of obtaining a large value of $w_{MG,G} \cong w_G \sim 10^{-12}$ is connected with the assumption of the sharp anisotropy of the cosmic rays in metagalactic space.

In[1,2] we expressed the opinion (in particular, in connection with[16]) that no noticeable anisotropy of cosmic rays can take place in metagalactic space. This statement, however, was not corroborated with concrete estimates, and recently a model with an ordered metagalactic field was proposed[17] (see also[18]), in which the assumption of the anisotropy of the cosmic rays in the metagalaxy seems at first glance perfectly plausible.*

Thus, the question of the anisotropy of cosmic rays turns out to be very important and calls for a detailed analysis. In the next section we shall discuss this question and corroborate our conclusion that no anisotropy is possible. If one is to agree with this conclusion, then the only real possibility of saving the metagalactic theory of the origin of cosmic rays in our Galaxy is to forego the inequality (3), at least in the region near our Galaxy, and, more concretely, to assume that

$$w_{\mathrm{MG}} = w_{\mathrm{G}} \sim 10^{-12}\ \mathrm{erg/cm^3} \qquad (4)$$

This is just the assumption made, as is well known, in metagalactic theories. We have listed above the arguments against such a possibility, at least when speaking of all metagalactic space. In addition to the foregoing, let us stop to discuss [19], in which the possibility of satisfaction of (4) is admitted, but unfortunately without taking our criticism[1,2] into account. Specifically, it is proposed in [19] that the cosmic rays enter the metagalaxy from radiogalaxies, and the average energy release during the explosion of a radiogalaxy is assumed to be 10^{62} erg. This value is unjustified and seems to us to be more likely overestimated by 2–3 orders of magnitude. The mechanisms proposed in [19] for the acceleration of cosmic rays as they collide with the "jets" (expanding magnetized clouds ejected by the radiogalaxies) is utterly ineffective[20]. In fact, even if the dimensions of the jets of matter produced during explosion of a galaxy are $l \sim 200$ kpsec

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*This conclusion is perfectly analogous to the conclusion which we drew concerning cosmic rays far from the Earth, by observing them inside the Earth's magnetosphere.

*In such a model, as also in[16], cosmic rays which are isotropic in the region of the field H_G (Galaxy) go into the intergalactic space with field $H_{MG} = \ll H_G$ conserving the adiabatic invariant $\sin^2\theta/H = \mathrm{const}$. There is therefore a strong anisotropy in the Metagalaxy ($\theta_{\max} \cong \sqrt{H_{MG}/H_G}$) and $w_{MG}/w_G \cong H_{MG}/2H_G$. For $H_{MG} \sim 3 \times 10^{-9}$ we have $H_G \sim 3 \times 10^{-6}$ and $w_G \sim 10^{-2}$ erg/cm^3, hence $\theta_{\max} \sim 1°$ and $w_{MG} \sim 10^{-15}$ erg/cm^3.

$= 6 \times 10^{23}$ cm (these are the observable dimensions of the radio-emitting regions in one of the largest radiogalaxies, A-Centauri) and the concentration of the galaxies is $N_{RG} \lesssim 10^{-78}$ cm^{-3}, then the relativistic particle experiences an average of one collision in the time $\tau \cong 1/l^2 N_{RG} c \cong 10^{20}$ sec $\cong 3 \times 10^{12}$ years. Therefore there can be no talk of a considerable increase in the energy of metagalactic cosmic rays (resulting from the mechanism discussed in [19]) within the characteristic time of evolution of the Metagalaxy $T_{MG} \sim 10^{10}$ years.

In order not to return to the problem of metagalactic cosmic rays, let us summarize the foregoing. If the cosmic rays in the intergalactic space cannot be strongly anisotropic (we shall present in Sec. 3 a rather convincing argument in favor of this conclusion), then the metagalactic theory of the origin of the bulk of the cosmic rays in our Galaxy can be saved only if the relation $w_{MG} \sim w_G \sim 10^{-12}$ erg/cm^3 is satisfied (see (4)). All the known data offer evidence against such a possibility and in favor of inequality (3). However, there is still no complete and irrefutable assurance of the correctness of this inequality, especially with respect to the nearest vicinity of our Galaxy. The point is that many of the arguments advanced concern in fact only the estimate of w_{MG} in the entire line of sight (for example, when we spoke of the flux of metagalactic γ-radiation, we had in mind the formation of radiation on a path of 5×10^{27} cm, corresponding to the photometric radius of our Metagalaxy; see [1,2]). Therefore it is still difficult to refute decisively the assumption that $w_{MG} \sim w_G$ in any vicinity of our Galaxy, whereas on the average $w_{MG} \ll w_G$ for our Metagalaxy. On the other hand, not only are there no real grounds for such an assumption, but this assumption in turn meets with serious objections (see [1,2]).

This being the situation, and, of course, taking into account the fundamental importance of this problem, further research is necessary. We can point here to the methods of radio-, gamma-, and x-ray astronomy, to the determination and refinement of the parameters of the intergalactic medium, and also to the possibility of obtaining more exact theoretical estimates.

3. COSMIC RAYS AND PLASMA PHENOMENA

The understanding of many insufficiently clear problems in astrophysics of cosmic rays is most closely connected, in our opinion, with allowance for plasma phenomena. Of course, the plasma character of the cosmic medium is universally known, and so that the statement made in general form is sufficiently evident —it is contained in [2] and perhaps in many other articles (see, in particular, an analysis of certain cosmic plasma effects in [21]). We have in mind here, however, more concrete remarks connected with allowance for the two-stream and other instabilities in a rarefied plasma as applied to the question of interest to us[22].

Let us consider for concreteness the following possibility: the magnetic field goes out of the galaxy into the metagalactic space in a smooth manner (expansion of the force tube) in the absence of any field homogeneities, wave fronts etc. Under such conditions the cosmic rays which are isotropic (or quasi-isotropic) in our Galaxy will move with conservation of the adiabatic invariant and, as indicated above, will form in the Metagalaxy a beam moving practically along the field. But such a case is the classic example of development of two-stream instability. It is essential here that the plasma frequency of the "parent" (metagalactic) plasma and of the beam itself are very high compared with $1/T_G$, where T_G is the characteristic time of evolution of the galaxy or even the time of explosion of the radiogalaxy. In fact, we present without further explanation, using the universally known expressions (see, for example, [23]), some values for the intergalactic plasma with electron density $n \sim 10^{-5}$. In this case, the plasma frequency is $\omega_0 = (4\pi e^2 n/m)^{1/2} = 5.64 \times 10^4 \sqrt{n} \sim 10^2$, while the Debye radius is $D = (kT/4\pi e^2 n)^{1/2} \cong 5\sqrt{T/n} \sim 5 \times 10^5$ cm (at temperature $T \sim 10^5$ °K). Under the same conditions the number of collisions between electrons and ions is

$$\nu = \frac{5{,}5n}{T^{3/2}} \ln (220Tn^{-1/3}) \sim 10^{-11} \text{ sec.}$$

In a field $H_{MG} < 10^{-7}$ the gyrofrequency is $\omega_H = eH/mc = 1.76 \times 10^7 H < 10$ sec^{-1} and thus $\omega_0^2 \gg \omega_H^2$. Even from these figures it is clear that weakly damped $(kD = (2\pi/\lambda)D \ll 1)$ plasma waves can propagate in metagalactic space. Further, even for a flux of cosmic rays with concentration $N_{c.r} \sim 10^{-13}$ (in the Galaxy $N_{c.r} \sim 10^{-10}$, and a value $N_{c.r} \sim 10^{-13}$ with the spectrum remaining constant corresponds to a density $w_{c.r} \sim 10^{-15}$ erg/cm^3) the plasma frequency of the beam is

$$\omega_s = (4\pi e^2 N_{c.r.} c^2/E)^{1/2} \sim 5 \cdot 10^4 \sqrt{\frac{N_{c.r}\, m}{M}} \sim 5 \cdot 10^{-4}$$

(the total energy is here $E \sim Mc^2 \sim 10^9$ eV, corresponding to protons which make the main contribution to $w_{c.r}$). It is obvious that of the ratio $\frac{2\pi}{\omega_s T_G} \sim \frac{10^4}{T_G}$ is exceptionally small. More important, of course, is the fact that the ratio $1/\gamma T_G$ is also small, where γ is the increment for the plasma oscillations resulting from the two-stream instability. The value of γ for the case just discussed was recently estimated in [24] precisely for these values of the parameters* and under the assumption that the velocity scatter in the beam is $v_{TS} \sim c$. In this case $1/\gamma_{max} \sim 30$ years. In fact, $\gamma_{max} \sim \omega_s^2/\omega_0$, and the largest increment corresponds to waves for which $kc \sim \omega_0$ (for the shortest

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*In order not to clutter up the exposition, we refer here, in addition to the already cited articles[21,22,24], where reference to more papers is made, also to the review[25], which deals specially with plasma turbulence, and also to the articles[26,27].

weakly-damped waves $kv_T \sim \omega_0$ or $kD \sim 1$, leading to a value $\gamma_{\min} \sim \frac{\omega_s^2}{\omega_0} \frac{v_T^2}{c^2} \sim 10^{-4} \gamma_{\max}$, $\frac{1}{\gamma_{\min}} \sim 3 \times 10^5$ years). Taking the magnetic field into account, the beam will generate also waves of other types, which, at least in the first stage, can only increase the growth rate of the perturbations in the plasma. Incidentally, in the absence of a field the two-stream instability does likewise not reduce to the generation of transverse waves only.

Further, at the border of a galaxy (and especially a radiogalaxy) we can expect concentrations $N_{c.r}$ even several orders of magnitude higher than the employed probable maximum metagalactic value of $N_{c.r} \sim 10^{-13}$.

Thus, an impression is gained that cosmic rays with a sharply anisotropic distribution function should become rapidly isotropic as a result of the growth of the oscillation amplitude. Unfortunately, we cannot draw any final conclusions (at least by considering only two-stream instability), because the nonlinear phase of the process is not clearly understood and also because of lack of data with which to take into account the effects produced on cosmic-ray beams by those waves which are produced by other sources.

Let us explain these remarks. It is customarily assumed (and for a beam of nonrelativistic particles this is apparently valid) that the development of two-stream instability leads to the formation of a "plateau" in the particle velocity distribution (as is well known, in the one-dimensional case, the beam is unstable only if its velocity spectrum contains a certain maximum at $v \neq 0$; therefore the instability disappears upon formation of the plateau). During formation of the plateau, plasma waves are generated, and the total energy is comparable with the initial energy of the beam. In addition to the tendency towards formation of a plateau, the beam becomes isotropic, since it is precisely the anisotropic distribution of the particle velocity which is unstable, while for a particle distribution that is spatially isotropic even the presence of a maximum in the energy spectrum (or velocity spectrum) does not lead to instability. From this point of view, at the relatively large values of the increment γ for the growth of the two-stream instability indicated above, one should indeed expect rapid isotropization of the cosmic rays and a tendency towards formation of a plateau in the spectrum of their energy distribution. At the same time, one must not regard such conclusions as unavoidable, even if the values of γ obtained in the linear approximation are quite large. The point is that under certain conditions, especially for relativistic beams, the nonlinear interaction of the waves may lead to stabilization of the beam[26,27]. Physically this is connected with a process that occurs in the nonlinear approximation, viz., the transfer of the waves generated by the beam to the nonresonant part of the spectrum, in which the waves do not interact directly with the beam (if the wave phase velocity $v_{ph} = \omega/k > c$, then such waves can obviously not be absorbed by the beam particles). On the other hand, the isotropization of the beam occurs not only under the influence of the waves generated by the beam itself, but also under the influence of waves (with $v_{ph} < c$) formed by arbitrary other sources and by cosmic rays present in the region through which the beam in question passes*. Under cosmic conditions, there are quite a few sources of different waves (beams emitted by stars, drift of cosmic plasma under the influence of gravitational and magnetic-field forces, etc.) but we are still unable to estimate the intensity of such waves.

Thus, there are many unclear factors in the question of the efficiency of isotropization of the cosmic rays as a result of two-stream instability in an isotropic plasma and under the influence of plasma or other waves from other sources. This uncertainty with respect to the fate of the cosmic-ray beams will apparently be greatly reduced if account is taken of the existence of a not yet mentioned periodic anisotropic instability: the anisotropic distribution of the particles in a magnetic field is, generally speaking, unstable even when without the effect of plasma waves; as a result of such an instability, the flux lines of the field bend and, in fact, the field become turbulized. The criterion for the anisotropic instability is as follows (there exist also instabilities of other types, which occur even when condition (5) is not satisfied):

$$w_{c.r,\,\parallel} - \frac{1}{2} w_{c.r,\,\perp} > \frac{H^2}{8\pi}, \tag{5}$$

where

$$w_{c.r.,\,\parallel} = \frac{MN_{c.r.}}{2} \overline{v_{\parallel}^2}, \qquad w_{c.r,\,\perp} = \frac{MN_{c.r}}{2} \overline{v_{\perp}^2},$$

$v_{\parallel}$ and $v_{\perp}$ are respectively the cosmic-ray velocity components parallel and perpendicular to the field (we use the nonrelativistic expression, something which can hardly lead to a noticeable error, inasmuch as $E - Mc^2 \sim Mc^2$ for the main part of the cosmic rays).

When the particles go over from the Galaxy into the Metagalaxy, conserving the adiabatic invariant, as already indicated, $w_{c.r\parallel} \cong w_{MG} \gg w_{c.r\perp}$, with $w_{MG} \simeq \frac{H_{MG}}{2H_G} w_G \sim \frac{H_{MG}H_G}{16\pi} \gg H_{MG}^2/8\pi$. Thus, criterion

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*In addition, depending on the spectrum of the plasma waves and the waves of other types, the cosmic rays can become accelerated (see[21] and Sec. 4) or slowed down as a result of absorption and emission of these waves. We note that as a result of scattering of waves by cosmic-ray particles, the latter are slowed down under the conditions of interest to us—this process is analogous to synchrotron radiation and Compton energy loss. Then $dE/dt = -bw_nE^2$, where b is a coefficient similar to that used for synchrotron radiation and Compton losses (see[1,2]), and w_n is the wave energy density in the plasma. Inasmuch as in the case of interest to us we apparently always have $H^2/8\pi \gg w_n$, the synchrotron radiation losses are more appreciable than the losses due to scattering by plasma waves.

(5) will be satisfied with a large "margin" (for example, when $H_{MG} \sim 3 \times 10^{-8}$, we have $w_{MG} \sim 3 \times 10^{-15}$ and $H^2_{MG}/8\pi \sim 3 \times 10^{-17}$). The growth increment of the discussed field perturbations is

$$\gamma_a \sim \left(\frac{w_{MG} - H^2_{MG}/8\pi}{MN_{c.r}}\right)^{1/2} k \sim ck,$$

since $w_{MG} \sim N_{c.r} Mc^2$. Further, the wavelength of the perturbation should exceed the gyroradius of the cosmic rays

$$r_H \sim \frac{Mc^2}{eH} \sim \frac{3 \cdot 10^6}{H_{MG}} \sim 10^{14} \text{ cm}$$

(for $H_{MG} \sim 3 \times 10^{-8}$). Consequently, $\gamma_a \lesssim 2\pi c/r_H \sim 10^{-3}$ and $1/\gamma_{max} \sim 10^3$ sec (!). The plasma waves which result from the two-stream instability discussed above can apparently only accelerate the field-turbulization process and the isotropization of the beam.

It is clear therefore that if the cosmic-ray beam were to reach the metagalactic region (the region where $H \sim H_{MG} \lesssim 3 \times 10^{-8}$) without isotropization and without loss of the ordered structure of the field which we have taken as our basis above, both these processes will occur very rapidly. But this means that the regular picture of the expansion of the force tubes of the field is unrealistic under such conditions, and in fact there should be produced a transition region in which the field, if it were regular in the galaxy, would become turbulent and the flux of cosmic rays becomes isotropic. By the same token, if a new batch of cosmic rays is produced in some galaxy (say, as a result of explosion of a galactic nucleus) these cosmic rays would become rather rapidly "self-isolated"—they surround the region occupied by them with a turbulent layer which prevents a rapid outflow of the cosmic rays into the surrounding space with weak field.*

It is precisely for this reason, from the point of view discussed here, that radio-emitting clouds are observed in the radiogalaxies, and there is no simple outflow of cosmic rays along the field lines. Of course, the above-mentioned "clouds," containing isotropic cosmic rays, can expand and move as a unit, as was indeed observed. Indeed, some diffusion outflow of the cosmic rays is possible also in the presence of a turbulent layer bounding the system (Galaxy, "cloud" in a radiogalaxy, supernova shell).

Unfortunately, no reliable estimate of the coefficient $D_{c.r}$ of diffusion through the aforementioned turbulent layer is possible without a more detailed picture and without taking into account all the essential instabilities, the nonlinear wave interaction, etc. (see [25]). By way of a minimal value of $D_{c.r}$ we can apparently consider the expression

$$D_{c.r, \min} \sim \frac{r_H c}{3} \sim \frac{Mc^3}{3eH} \sim \frac{3 \cdot 10^{16}}{H}$$

(we have in mind a particle with energy $E \sim Mc^2$). The value obtained in this manner for the Galaxy $D_{c.r.min} \sim 10^{22}$ cm^2/sec (for $H_G \sim 3 \times 10^{-6}$) is much lower than the coefficient $D_{c.r} \sim 10^{28}-10^{29}$ used in [2]. There is still no contradiction here, however, since the field in the turbulent region is weaker than in the Galaxy as a whole and the coefficient $D_{c.r}$ can still be appreciably larger than $D_{c.r.min}$.

One way or another, the appearance of a turbulent layer in the region of transition from the strong field to the weak field undoubtedly helps explain the retention of the cosmic rays in the supernova shells, in the Galaxy, and in the radio-emitting regions (clouds) in radiogalaxies. In particular, as applied to our Galaxy, we can assume the characteristic time of emission of the cosmic rays from the system to be $T_e \sim 3 \times 10^8$ years, since this value still does not contradict the data on the chemical composition of the cosmic rays (see Sec. 4).

As already seen, there are grounds for expecting effective isotropization of the cosmic rays as a result of the joint action of the different mechanisms of the instability of the anisotropic distribution of the particles; so long as the isotropization process is not yet complete, smoothing of the energy distribution function also takes place*.

By virtue of the foregoing we must think that the cosmic rays that fall into the intergalactic space from the galaxies will become rapidly isotropic in a transition region near the galactic "boundaries." For this reason, even disregarding the possible isotropization in the metagalactic space itself, the metagalactic cosmic rays should be practically isotropic, as was assumed at the end of Sec. 2.

The process of isotropization of the cosmic rays that are produced, say, in the explosion of galactic nuclei and are sharply anisotropic during some stage (this always occurs in the case of regular influx of cosmic rays into a region with a weaker ordered field), is accompanied by generation of various wave types. The total energy which goes over into these waves (in particular, plasma waves) is probably of the same order as the total energy of the produced cosmic rays. During the course of propagation of the waves in metagalactic space, they heat by collision the intergalactic gas. Effective heating of the gas occurs also as a result of ionization losses of the subcosmic rays (par-

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*If we mean the outflow of cosmic rays through the arms of the galactic spiral then, from the point of view discussed here we should speak of the formation of turbulent "mirrors" that prevent the cosmic rays from leaving the arm. Of course, the turbulent layer is produced gradually and some fraction of the cosmic rays will leave the system without encountering any special obstacles.

*We do not discuss here cosmic rays of solar origin, for which rapid processes are essential and the isotropization may make no noticeable progress. However, the foregoing remarks must be taken into account, of course, also in the analysis of solar cosmic rays.

ticles with energies $E_c < 10^8$ eV), the generation of which is quite probable. Calculations[24] lead in this case to the conclusion that, roughly speaking, $nkT \sim w_{MG} + w_{sc.r}$ (here T is the temperature of the intergalactic gas with concentration n, while w_{MG} and $w_{sc.r}$ are the energy densities of the cosmic and subcosmic rays in the metagalactic space). From this we get for $n \sim 10^{-5}$ and $w_{MG} + w_{sc.r} \sim 10^{-15}$—$10^{-16}$ a temperature $T \sim (w_{MG} + w_{sc.r})/kn \sim 10^5$—$10^6$ °K. Thus, within the framework of evolutional cosmology (the calculations of [24] are based on this assumption) the temperature of the intergalactic medium can and probably should be high even in spite of the cooling due to the general expansion of the Metagalaxy. Within the scope of the present article, another conclusion is more important: If condition (4) were to be satisfied, that is, if the energy density w_{MG} were to be of the order of $w_G \sim 10^{-12}$, and the cosmic rays would be supplied by galaxies and radiogalaxies (as is usually assumed in metagalactic theory of the origin of cosmic rays; see [19]), then one could expect heating of the intergalactic gas to a temperature $T \sim \frac{w_G}{kn} \sim 10^9$ °K. Yet, from the data on the background of the cosmic x-rays, it follows[28,29] that the temperture is $T < 3 \times 10^6$ deg (if we use the estimate $T \sim w_{MG}/kn$, then we get from this $w_{MG} < 3 \times 10^{-15}$ erg/cm^3). Measurements of the x-ray background for wavelengths reaching 50 Å will make it possible to establish the value of T, if it is not lower than 4×10^5 °K (see [30]). The use of the estimate $T \sim w_{MG}/kn$ and the x-ray data is connected, of course, with certain additional assumptions. There is no doubt, however, that in such a way we obtain an additional argument in favor of the correctness of the inequality $w_{MG} \ll w_G \sim 10^{-12}$.

The practice of taking plasma effects into account in the astrophysics of cosmic rays is barely beginning, yet it is connected with appreciable difficulties. This is precisely why some of the considerations presented above have not been sufficiently well developed and we can more readily speak of guesses and a research program than of fully defined conclusions. Nonetheless, in our opinion, even now there are all reasons for assuming that the analysis of plasma phenomena is of fundamental significance for further development of the astrophysics of cosmic rays (the same, apparently, also applies to quasars; see [59]).

4. REMARKS ON CERTAIN QUESTIONS OF THE ASTROPHYSICS OF COSMIC RAYS

In this section we make several remarks on questions to which we cannot allot more space, or with respect to which there are still few data.

One such question, which is of fundamental significance not only for astrophysics of cosmic rays but also for the theory of solar flares and radiation belts, is the problem of acceleration of particles to high energies. As is well known[2], the statistical mechanism (the Fermi mechanism) is ineffective when applied to interstellar space, if use is made of the available data on the velocity and dimensions of the characteristic inhomogeneities (clouds) in the interstellar medium. In addition, the assumption of interstellar acceleration of cosmic rays is connected with difficulties with respect to the energy. Therefore, in the galactic theory of the origin of cosmic rays, the main sources are considered to be supernovas and flares from the galactic nucleus. At the same time, the question of interstellar acceleration (or additional acceleration) can not yet be regarded as finally solved. Thus, in the presence of plasma and other waves in the interstellar medium, with sufficiently high energy density (but one still small compared with the thermal energy of the medium), the interstellar acceleration may turn out to be effective[21]. This assumption is worthy of attention, but questions concerning the sources of such waves, the power transferred, the maximum energy and the maximum energy density of the particles still remain unanswered. We note, in addition, that in the case of interstellar acceleration in the entire volume occupied by the cosmic rays, the thickness of matter traversed by the cosmic rays will increase with energy. We shall show below that the experimental data offer no evidence in favor of such a possibility.

Thus, even when plasma effects are taken into account, there are still no grounds for foregoing the assumption that the main source of the cosmic rays in our Galaxy are supernova explosions and possibly explosions of the galactic core. The acceleration mechanism in such a process is still insufficiently clear. In principle the regular or statistical acceleration in turbulent magnetic fields may be effective here. However, a study of solar flares, which possibly simulate, at least in part, phenomena occurring during explosions of supernovas and even radiogalaxies, shows that the probable particle acceleration mechanism is direct transformation of magnetic energy into fast-particle energy under conditions when the "freezing-in" of the magnetic field is violated. A possible mechanism of such an acceleration was considered in [31]. A study of the generation of fast particles in solar flares is now the most promising way of explaining the nature of cosmic accelerating mechanisms, for in this case we can obtain incomparably much more information than for remote sources.

From the point of view of energy, the generation of cosmic rays during supernova explosions raises, in our opinion, no serious difficulties. In addition to the statements made in Sec. 1, it should be noted that in connection with an overestimate of the distances[32], the power of supernovas of type I turns out to be much higher than assumed in [2], and becomes of the same order as the power of supernovas of type II. As a result, the cosmic-ray energy contained in the shells of the supernovas of types I and II turns out to be of the order of (1—3) × 10^{49} erg. On the other hand, the total energy of the cosmic rays produced as a result of the explosion can and apparently should be even larger, since cosmic rays leave the system all the time. The upper limit of the total energy of the cosmic rays is of the order of the total energy of the explosion, which reaches 10^{51}—10^{52} erg. Yet even the maximum value for an injection power $U_{c.r} = 10^{41}$ erg/sec (see (2)), using the minimum estimate for the frequency of flares in the Galaxy (one every three hundred years), is found to be, when converted in terms of cosmic rays, 10^{51} erg per flare. Within the framework of galactic theory of the origin of the cosmic rays observed on Earth, we have, in addition, a "reserve" source—explosions of the galactic nucleus, the contribution of which is still unknown (for more details, see [1,2,5,13,13b] and the literature cited there. We note that in the case of powerful and infrequent explosions of the core we would deal with a nonstationary galactic theory of the origin of cosmic rays[1,2,20,33]. We still see no direct argument favoring such a possibility; we can indicate, however, a few possibilities for checking the nonstationary model (see [1] and below).

Great interest attaches to the question of the energy spectrum of the cosmic rays and their radio-emitting electronic components. It was established in [3] that the spectral radio-emission indices of extragalactic objects cluster, with small dispersion, about the value $\alpha = 0.76$. This is sometimes regarded as an indication of the existence of a single reservoir of cosmic rays (we have in mind our Metagalaxy) from which the cosmic rays fall into the galaxies and, consequently, have the same energy spectrum everywhere. In addition to the statements made in Sec. 2 with respect to the difficulties of the metagalactic theory of the origin of cosmic rays, it should be noted that there is no need for assuming the existence of such a common reservoir. The point is that under the conditions of "equipartition" of the energy between the cosmic rays, turbulence, and the magnetic field (see (1)), the spectrum of the cosmic rays which emerge from the sources (supernovas, region of galactic nucleus) has a universal value[2,10] $\gamma = 2\alpha + 1 \cong 2.5$. No limitations are imposed here on the spectrum in the sources themselves—this spectrum can be arbitrary. The latter agrees with measurements[3] which offer evidence that the spectral indices of the galactic sources have an appreciably larger dispersion than those of the extragalactic sources (a characteristic example is the Crab nebula with radio index $\alpha \cong 0.25$).

Let us stop now to discuss briefly the chemical composition of cosmic rays, a study of which can yield much information on the sources, the character of the acceleration, and propagation of cosmic rays. As already mentioned, in this way one can estimate sufficiently reliably the average thickness of the matter traversed by the cosmic rays as they move in the galaxy (~ 2—10 g/cm^2, depending on the assumed parameters and the propagation model) and the composition of the sources. Subsequently, when more accurate data on the composition and parameters of the fragmentation are available, it will be possible to choose the propagation model (choosing primarily between the regular and diffusion models)[2], and to determine the age of the cosmic rays and the average density of matter in the region of their propagation[34], the character and duration of the acceleration[9,35,36], and also the dependence of the traversed thickness and diffusion coefficient on the energy[9,37].

It is difficult to reconcile the presently available data[20] on the chemical composition with the above-mentioned hypothesis that powerful and rare explosions occur in the region of the galactic nucleus and lead to the formation of the bulk of the cosmic-rays in one such explosion (the nonstationary galactic model). In fact, in such a model the particles traverse within a time T following the explosion a thickness $x = \rho v T$ g/cm^2, where ρ is the average density of the substance in the region of propagation of cosmic rays, and v is the particle velocity. It follows therefore that the nonrelativistic particles ($v < c$) should pass at the instant of observation through a smaller thickness of matter than the relativistic ones ($v \cong c$). Yet, from data on the chemical composition it follows that for nonrelativistic energies the fraction of L-nuclei (Li, Be, B) is larger[8,9,37] than for relativistic ones (see, however, the appendix). This apparently corresponds to a larger traversed thickness of matter precisely for the nonrelativistic particles, and would contradict the nonstationary model. More rigorous conclusions can be drawn only after taking into account the ionization losses and the character of propagation of the particles as functions of the energy (it is not excluded that the slow cosmic rays move essentially in the region of the disc, where the average density is higher, whereas the relativistic particles spend a considerable part of the time in the more rarefied field). The nonstationary model can also be verified by investigating the relative composition of the L-nuclei, He^3 and D in relativistic cosmic rays[37a].

The question of the nature of the electronic component of the cosmic rays has by now been clarified to a considerable degree. According to calculations[5] (see also Sec. 17 of the English edition of the book [2]) the radio-emitting electrons in the Galaxy cannot have a secondary origin, and must be directly generated in the sources, as is the proton-nuclear component. This deduction agrees with the results of measurements of the fraction of positrons in the electronic component of cosmic rays.[38] Of particular importance presently is the measurement of the spectrum of electrons in the energy region E > 3—10 GeV which, at least at present, cannot be deduced from radioastronomical data (see also the appendix).

Let us stop to discuss briefly gamma and x-ray astronomy and their connection with the astrophysics of cosmic rays (for more details see [11]). The possibility of estimating the concentration of relativistic electrons in our Metagalaxy, by starting from the intensity of the Compton γ-rays, makes gamma-astronomy an indispensable means of investigating cosmic rays in our Metagalaxy (see Sec. 2). With respect to discrete sources of γ rays, it is of interest to realize the possibility indicated in [39] (see also [13]) of registering γ rays produced in the quasar radio-source 3C 273-B by Compton scattering of optical photons by relativistic electrons in this source. In connection with new data[40] on the infrared radiation from 3C 273-B and the corresponding increase in the total luminosity of this object, the expected γ-ray flux can be higher than the estimate obtained in [39] $F_\gamma(E_\gamma \gtrsim 3\text{ MeV}) \cong 5 \times 10^{-6}$ photons/cm^2 sec.

Ordinary galaxies are not anomalously strong γ emitters[11] (this pertains[12] also to the galaxy M-82, in which an explosion of the core has been observed).

In the field of x-ray astronomy the initial optimism, connected with the hope of observing hot neutron stars, has now greatly abated. This is connected, first, with the large dimensions of the x-ray source in the Crab nebula[41] and, second, with a clarification of the fact that neutron stars (if we disregard accretion[42]) apparently cool down much more rapidly[43,44] than has been assumed previously. The observations of x-ray emission from neutron stars, of course, is not excluded, but it is probable that not only the Crab nebula but also other observed cosmic sources of x-rays are not neutron stars. It is most probable that the x-ray emission from these sources has a synchrotron radiation nature[11,32]. Nonetheless, in accordance with [45,46], a bremsstrahlung mechanism of cosmic x-ray emission is not yet excluded. Under such conditions, the most convincing proof of the synchrotron-radiation character of the x-ray emission would be observation of its polarization (such polarization measurements, albeit complicated, are perfectly feasible in principle).

This paper has been separated from its predecessor[1] by a lapse of less than two years. Nonetheless, during that time, not only has definite progress been made in the field of theory and experiment, but the exceedingly important role of cosmic rays in astrophysics has been made quite clear.

APPENDIX

The present appendix was written following the Ninth International Conference on Cosmic Rays (London, September 1965) and reflects some of its results, and also new data and considerations pertaining directly to this paper.

We note first that, with respect to the theory of the origin of cosmic rays, no new evidence has been presented at the conference in favor of the metagalactic origin of galactic cosmic rays (if we disregard the highest energies). To the contrary, in a highly informative article, E. Parker develops ideas on the influence of cosmic rays on the dynamics of the Galaxy, which are very close to those contained in our paper; in particular, he emphasizes the role of instability in the occurrence of the boundary galactic halo and in the isotropization of the cosmic rays which emerge from the Galaxy into the Metagalaxy.

Many new experimental data, which greatly add to our knowledge of the origin of cosmic rays and their electronic component, have been reported to the conference. We must point first to data on the energy spectrum and the intensity of primary electrons. In a review paper by P. Meyer (see also [48]), the following value is given for the intensity of the electronic component in the energy interval $0.5 < E < 3$ GeV:

$$I_e(E) = 1.1\cdot 10^{-3}\cdot E^{-1.6}\ \text{electron/cm}^2\text{sec-sr-GeV}.$$

The exponent in the spectrum is established here with accuracy ± 0.5. Such a spectrum is much more gently sloping than the spectrum of the proton-nuclear component of cosmic rays (for all cosmic rays, the exponent in the differential energy spectrum is equal to $\gamma \cong 2.6$). This circumstance, which is already made quite clear by analysis of the spectrum of the overall galactic radioemission, raises even more acutely the question of the sources and the mechanism of acceleration of relativistic electrons in the Galaxy.

The new data (with the exception of the preliminary results presented in the paper of Daniel and Stevens for energies $E > 15$ GeV) confirm the previous deduction that an excess of electrons is present in the electron-positron component.

A certain difficulty is noted with respect to the absolute value of the electron intensity, which turns out to be several times smaller than that necessary to explain the overall radioemission of the Galaxy[1,5]. If, as follows from present-day notions on the modulation of the intensity of cosmic rays, the attenuation of the intensity of the electrons on Earth, compared with their intensity outside the solar system, is immaterial, then a way out of this difficulty can be found by taking into account the inhomogeneity of the galactic magnetic field and the contribution of regions with increased particle density (radio measurements with high angular resolution offer evidence that the distribution of the radiobrightness over the sky is essentially inhomogeneous).

Many new data were also presented at the conference on the chemical composition and the energy spectrum of the cosmic rays, and also on solar modulation in the region of low energies. Let us stop first to discuss the energy dependence of the ratio L/M of the intensities of nuclei of the L and M groups. According to Balasubrahmanian et al., $L/M = 0.18 \pm 0.05$ for $E = 100$ MeV/nucleon and $L/M = 0.30 \pm 0.03$ for $E > 600$ MeV/nucleon. These results contradict the already mentioned data of [8,9,37]. Thus, the question of the ratio L/M as a function of the energy is not yet answered either experimentally or theoretically (the latter was emphasized in the text). Therefore, the possibility of checking the hypothesis of infrequent and powerful explosions in the Galaxy by analyzing the chemical composition in the nonrelativistic-energy region still remains open. At the same time, this hypothesis is in distinct contradiction to the statement, made in the paper by D. Dahl on the basis of meteoritic data, that the intensity of the cosmic rays has remained unchanged during the last billion years (within ± 50%).

Very interesting results have been reported (J. Simpson et al.) on the spectra of nuclei with different Z in the energy region $E < 300$ MeV/nucleon. What was unexpected was the absence of a maximum in the spectrum of nuclei with $Z > 2$, although such a maximum exists for protons (at $E \sim 300$ MeV). In this connection, special interest attaches to the problem of the high-latitude cutoff in the energy spectrum of cosmic rays on Earth and to the question of the spectrum of galactic cosmic rays outside the solar system.

Let us make also a few additional remarks concerning some questions touched upon in the paper. Among the very important and at the same time insufficiently clear problems in radioastronomy and astrophysics of cosmic rays is the problem of construction and formation of galactic halos, and especially the halo of our own Galaxy. In 1963 there were published data[2,49], offering evidence against the existence of a noticeable radiohalo in the spiral galaxies NGC 253, NCG 4945 and NGC 5236. Both for this reason, and from other considerations[2,50], doubts arose regarding the existence of a well developed halo even in our own Galaxy. In a recent paper[51] it is shown, however, that each of the mentioned three spiral galaxies has indeed a clearly pronounced halo. Theoretical considerations, both those known for a long time (see [2] and the literature cited there) and some only just published[52], also offer evidence in favor of the unavoidable existence of a halo in the Galaxy. This circumstance is particularly important from the point of view of our paper, since the galactic theory of the origin of cosmic rays in the Galaxy is organically connected with assumption that a halo exists.

We have already pointed to different ways of confirming or refuting either the galactic or the metagalactic theories of origin of cosmic rays. We have left aside, apparently without any justification, data on the anisotropy of cosmic rays. In accordance with the considerations advanced in the paper (and also, incidentally, in the framework of the diffusion picture[2]) we cannot expect any strong anisotropy of cosmic rays. But if cosmic rays do flow in or out of the Galaxy, then some anisotropy, connected with the existence of a flux of cosmic rays, should take place. In the galactic theory we have an outflow, while in the metagalactic theory, to the contrary, we have an influx of cosmic rays into the Galaxy. By the same token, measurement of the sign of the anisotropy, that is, the direction of the flux, would be highly meaningful. To be sure, the magnetic field near the solar system can distort the picture, but it is very unlikely that the local field would reverse the sign of the anisotropy. According to data for the next to the last minimum of the solar activity (1954-55),[53] an anisotropy was observed of the order of several tenths of one per cent ($\delta = (I_{\max} - I_{\min})/(I_{\max} + I_{\min})$), the flux being directed from the center of the Galaxy to the periphery. This result was confirmed also for the last minimum of solar activity[54]. By the same token we have therefore one more argument in favor of the galactic theory[55], and, what is most important, this possibility appears to us quite promising for further research.

One method of verifying the hypothesis of formation of a considerable part of the cosmic rays (more accurately, their electronic component) during the time of powerful explosions of the galactic core is to study the electron spectrum. Whereas we have previously emphasized[1] this factor from the point of view of radioastronomical observations, we wish to note at present that it is simplest and more reliable to measure directly the spectrum of electrons on balloons and satellites. The electrons which were produced, say, 3×10^7 years ago, cannot have an energy larger than 10^{10} eV (see [1]). If this procedure or meteoritic data yield evidence against existence of powerful explosions of the galactic core* this would be simultaneously a certain argument against the local metagalactic theory of the origin of cosmic rays (in fact, in such a scheme the cosmic rays observed in the Galaxy are assumed to be produced near it, for example, upon explosion of some neighboring radiogalaxy; but under these conditions, the flux of cosmic rays in the Galaxy would be to some degree nonstationary and the electrons could have a more or less definite age, etc.). We emphasize that although we know of no arguments based on observations in favor of the local metagalactic theory, its discussion is nevertheless necessary (for more details, see Sec. 2 of the present paper).

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*We have already mentioned that meteoritic data offer evidence that the average flux of cosmic rays has been approximately constant during the last 10^9 years (see also[56]). According to the data of Rubtsov[57] the spectrum of electrons in the Galaxies is not cut off, at least up to an energy of 2×10^{10} eV.

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