The origin of cosmic rays (Forty years later)

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(Submitted 12 April 1993)
Usp. Fiz. Nauk **163**, 45–50 (July 1993)

Forty years ago the author published in "Uspekhi Fizicheskikh Nauk" the article "The origin of cosmic rays and radioastronomy." In it the galactic model of the origin of cosmic rays was developed. With this was associated the assumption of the small intensity of cosmic rays in the Metagalaxy. Such an assumption indicating the lack of validity of metagalactic models of the origin of cosmic rays has been confirmed only very recently. This has been accomplished with the aid of measurements on the gamma-observatory of the flux of gamma rays from the Magellanic Clouds. In this article the corresponding results are quoted and discussed.

In 1953, my article "The origin of cosmic rays and radioastronomy," was published in Uspekhi Fizicheskikh Nauk.[1] In it was given a summary of the activity developing in the USSR starting with 1951 (for references see Ref. 1) devoted to the nonthermal cosmic radio emission and in this connection to the origin of cosmic rays. The latter were discovered long before that—somewhat arbitrarily in 1912 (cf. Ref. 2). However, on the whole up to 1951–1953 there was no incentive to speak about elucidating the origin of cosmic rays and the development of the astrophysics of cosmic rays in view of the practically complete isotropy of primary cosmic rays near the earth (the action of terrestrial magnetic field being excluded). Indeed, the isotropy of the incoming radiation does not give a possibility of indicating its sources and their spatial distribution. The situation here is analogous to what would have taken place in optical astronomy if one studied only the total light from all the stars and the other celestial objects. Therefore the establishment of a connection between nonthermal cosmic radio emmision and the electron component of cosmic rays (we are speaking of the synchrotron radiation from relativistic electrons) has radically altered the state of affairs—it became clear that far from the earth there are some kinds of sources of cosmic rays. It is true that in so doing one has to assume that the concentration or the energy density of the principal proton-nuclear component of cosmic rays is, let us say, proportional to the corresponding values for the electron component. Also, generally speaking, it is necessary to know the intensity of the magnetic field in the emitting region. Nevertheless this does not prevent one from making considerable progress along the path of investigating cosmic rays far from the earth which is discussed in detail in the reviews of Refs. 1–5. We shall not repeat ourselves here since the aim of the present article is a different one—it is written in connection with the fact that only at the beginning of 1993, forty years after the publication of the article of Ref. 1, one of the principal assumptions made in it has been proven.[6] We have in mind the assumption concerning the galacatic, and not the metagalactic, origin of the principal part of cosmic rays observed near the earth (in addition to these cosmic rays there exists also a very weak solar component; moreover, we do not touch upon the relatively low-intensity cosmic rays with very high energy, say, exceeding 10^{15}–10^{16} eV). Ref. 1 was written in a state of certain euphoria associated with the breakthrough in the understanding of the entire problem due to the inclusion of radioastronomic data. The article of Ref. 1 concludes as follows:

"Thus, it is still necessary to elucidate a number of essential points before we can regard the problem of the origin of cosmic rays clear in all its aspects. But as it appears to us the main task here is completed and the picture outlined above will not undergo radical changes similar to those that occurred until very recent times up to the use of radioastronomical methods for clarifying this set of problems.

With the development of radioastronomy and also of cosmic electrodynamics the question of the origin of cosmic rays became a truly astrophysical problem and left the stage of primarily hypothetical constructions which could not be verified with the aid of observations. Therefore, and also taking into account the progress in the physics of cosmic rays, one can be confident that the further development of the theory of the origin of cosmic rays will move foreward rapidly."

In general–everything in this conclusion turned out to be correct except for the prediction of rapid progress. More accurately the picture presented in Ref. 1 is correct, but one had to wait many years for actual proofs. We have in mind three key statements:

1. It is the galactic, and not the metagalactic, model (theory) that is valid.

2. It is the galactic model with a large halo that is valid or, in any case, not the disk model in which the cosmic rays are concentrated in a certain disk with the half-thickness $h_d \sim 100$–300 pc.

 1063-7869/93/070587-05$10.00

3. The principal sources of cosmic rays in the Galaxy are supercovae.

These questions, with the exception of the last one, were slurred over in Ref. 1, but subsequently were actively discussed (see Refs. 2–5 and the literature cited therein).

With respect to the dominant role of the supernovae (statement 3) little has changed compared to Ref. 1. Indeed, two arguments were given. First, the energy release in supernovae is great and could be quite sufficient for the acceleration of the required amount of cosmic rays. Specifically, the average energy release in the flare-up of a single supernova is equal to $W_{SN} \sim 10^{49}$–10^{51} ergs without taking into account the energy carried away by the neutrinos (for the supernova SN 1987 A the energy release into neutrinos was of the order of 10^{53} ergs). If, as it is thought, supernovae in the galaxy flare up on the average every $t_{SN} \sim 30$ years then the average power (luminosity) of the Galaxy in cosmic rays may amount to $L_{G,cr} \sim W_{SN}/t_{SN} \sim 10^{40}$–$10^{42}$ erg/s. However an estimate of the luminosity $L_{G,cr}$ based on considerations of balance (cf., for example, Ref. 5, Ch. 1) leads to values of $(1\text{–}5) \cdot 10^{40}$ erg/s. Second, as is clear from radioastronomical data, in the envelopes of supernovae undoubtedly there are cosmic rays with their total energy being quite considerable (for details see Ref. 3, Table 7). These considerations retain their validity entirely. Moreover, the energy liberation in other classes of stars, generally speaking, is significantly lower than what is required. Finally, in addition it is difficult, if not impossible, apart from supernovae to accelerate particles to energies, say, of the order of 10^{15} eV. A new important aspect that became clear in 1977 and later is acceleration at the fronts of shock waves (cf., Ref. 5, Ch. 10). Such waves, particularly the most powerful ones, are formed exactly as a result of supernova flare-ups. Nevertheless, the question of the acceleration of cosmic rays by stars of different types of course remains. Even if the contribution of these stars to the overall energy balance is small (or even extremely small) the corresponding cosmic rays can play an observable role near the star (just such a situation exists in the case of the sun). Thus, the problem of the sources remains, but it lies, one can say, in the area of making the model of the origin of cosmic rays more precise and not of its foundations.

We now turn to the question of the halo, i.e., of an extended region surrounding the disk of the spiral Galaxy in which the energy density of cosmic rays and the radio brightness are more or less significant. In the former case we have in mind the halo of cosmic rays, and in the latter the radio halo. These are different concepts since the brightness of the radio halo, and thereby its effective size depend both on the concentration of relativistic electrons, and also on the intensity of the magnetic field. Therefore situations are conceivable when the radio halo is not great, while the cosmic ray halo is quite significant. From the physics point of view the existence of a halo, or, as it is sometimes said, a corona is obvious. Indeed, as is well known, for instance from the experience with thermonuclear research, it is quite difficult to retain charged particles in traps (tokamaks and others). So what is the point of speaking about natural "traps" that are incomparably less perfect? It is therefore clear that magnetic fields and cosmic rays emerge from the disks of galaxies and, in particular, of our Galaxy. Also some quantity of interstellar plasma emerges. We can directly observe in the first instance only the radio halo (although, the possibility is also realistic of observing a gamma-halo; cf., Ref. 5, Ch. 6). But in the case of our Galaxy the observations of halos and, in particular the radio halo is essentially made complicated in connection with the fact that we (the observers on the earth) are within the "system." As a result the problem of the radio halo of the Galaxy turned out to be the subject of controversy and evoked furious arguments.[7] Generally speaking, one can say that the question of the halo was not a lucky one (this gave me a pretext to refer to the problem of a halo as multifaced and long-suffering[8]), as a result for many years the model of the origin of cosmic rays with a large halo was also frequently ignored. The situation changed only in 1977 when there were observed clearly expressed radio halos for the galaxies NGC4631 and NGC891 seen "edge-on."[9,10] By the way, attempts were made to find the radio halo of the galaxy NGC4631 as a result of my conjecture even earlier,[11] but they were unsuccessful (this result seemed to be discouraging; apparently the reason was simply the insufficient sensitivity of the apparatus). Of course, the existence of a radio halo at least in a number of galaxies[9,10,12] does not yet say anything directly about the halo of our Galaxy. However the general doubts concerning radio halos no longer arise and in combination with the data for our Galaxy itself (cf., Ref. 5, Ch. 5) this has led, as far as I know, to the liquidation of arguments about the halo. According to my conviction that goes back to my article[1] only the galactic model of the origin of cosmic rays with a halo and even quite a large halo (the characteristic size is $R_h \sim 10$ kpc) deserves attention as a physical model. The disk models (in particular the so-called "leaky-box," or the homogenous model) have only an auxiliary significance, since they enable one to carry out a number of calculations more easily (cf. Ref. 5, Ch. 3). At the same time one should note that the parameters of the halo of our Galaxy are known only poorly, and it is urgent to determine them more precisely. For the time being one has to simplify the problem, to make assumptions and only after this to develop the theory of the origin of cosmic rays using the model with a halo.[5]

We now finally go over to the problem of refuting the metagalactic models, and this automatically signifies the necessity of using the galactic model (there is no alternative here, since the solar model that had been discussed some time ago in which the cosmic rays are concentrated in a certain near-solar region has been refuted long ago; cf., for example, Ref. 3.) At the first stage the main objection against metagalactic models had an energetic nature. The average characteristic energy density of cosmic rays in the Galaxy is

$$w_{G,cr} \sim 10^{-12} \text{ erg/cm}^3. \quad (1)$$

With a radius of the halo $R_h \sim 10$ kpc $\sim 3 \cdot 10^{22}$ cm the volume of the "system" (the halo of cosmic rays) is

$V_h \sim (4\pi/3)R_h^3 \sim 10^{68}$ cm^3 the total energy of the cosmic rays in the Galaxy is $W_{G,cr} \sim 10^{56}$ erg $\sim 10^2 M_\odot c^2$. The mass $M_{cr} \sim 10^2 M_\odot \sim 10^{35}$ g corresponding to cosmic rays is negligible compared with the mass of the Galaxy $M_G \sim 10^{11} \times M_\odot \sim 10^{44}$ g. However the kinetic energy of the random (peculiar) motion of all the stars is of the order of $K_G \sim 10^{11}\ M_\odot v_0^2 \sim 10^{56}$ erg $\sim W_{G,cr}$, since $v_0 \sim 10^6$ cm/s. In the metagalactic model the cosmic rays fill the entire metagalaxy more or less uniformly, i.e. (at least in the case of the red shift parameter $z < 1$)

$$w_{Mg,cr} \approx w_{G,cr} \approx 10^{-12}\ \text{erg/cm}^3. \quad (2)$$

Such a density corresponds to tremendous energy (for example in a volume with a radius of only 1 Mpc $W_{Mg,cr} \sim 10^{62}$ erg) and it is difficult to generate it. This question has been discussed in some detail in the book of Ref. 3. Here it is sufficient to note that within the framework of evolutionary cosmology about which at present there are no doubts, it is natural to expect that the inequality

$$w_{Mg,cr} \ll w_{G,cr} \sim 10^{-12}\ \text{erg/cm}^3, \quad (3)$$

is valid and specifically it is probable that $w_{Mg,cr} \lesssim 10^{-15}$–$10^{-16}$ erg/cm^3. But metagalactic models did have,[13] and possibly still have adherents.

In any case it is desirable to prove directly the validity of the inequality (3) and thereby to refute the metagalactic models.

The first real success along this path is associated with the discovery in 1965 of metagalactic relict thermal radiation with a temperature of 2.7 K. The energy density of this radiation is $w_{ph,T} \approx 4 \cdot 10^{-13}$ erg/cm^3. Relativistic electrons moving in the radiation field and a magnetic field of intensity H undergo energy losses (by the inverse Compton effect and by synchrotron radiation respectively) proportional to $w_{ph,T} + (H^2/8\pi)$. As a result, as can be easily shown (cf. Ref. 5, Ch. I), electrons with an energy of $E_e \gtrsim 10^{10}$ eV, and possibly, also $E_e > 10^9$ eV will not be able to reach the Galaxy and, in particular, the solar system, even from the nearest radio galaxy Centaurus A (distance is $R \approx 4$ Mpc). In the case of being scattered by the intergalactic photons of the relict radiation the electrons generate x rays and gamma radiation. The intensity of this radiation if the electrons in the Metagalaxy were present with the same intensity and spectrum as in the Galaxy would have been considerably higher than the observed one.[30] Thus, the electron component of cosmic rays in the Galaxy, at least in the case of not too low energies, must be of galactic origin. From this, naturally, the same is also true with respect to the proton-nuclear component.[14]

Nevertheless it is especially desirable to prove directly the validity of the inequality (3). This can be done in two ways. First, we have in mind measurement of the flux of gamma rays from the Magellanic Clouds.[15,16] Secondly, we have in mind measurements also by a gamma-astronomical method of the gradiant of the concentration of cosmic rays in the Galaxy.[17] Indeed, in the galactic model the energy density toward the periphery of the Galaxy must fall off and approach the value $w_{Mg,cr}$. Such measurements, or, more accurately, the appropriate treatment of the gamma data, has already been carried out. Some indications of the presence of a gradiant of the intensity of cosmic rays have been obtained, but on the whole the data in this respect are insufficiently definite (Ref. 5, Chs. 1 and 6). As regards the gamma radiation from the Magellanic Clouds it has most recently been measured[6,18,19] and this actually was the impetus for writing this article.

Collisions of cosmic rays—protons and nuclei with nuclei of interstellar gas—give rise to π^0 mesons which practically instantaneously decay with the formation of two gamma photons (the $\pi^0 \to 2\gamma$ channel). If the π^0 meson is at rest, the photon energy is $E_\gamma = (1/2)m_{\pi 0}c^2 = 67.5$ MeV. In the case of π^0 mesons formed by cosmic rays of course a certain gamma spectrum is generated. Obviously, the intensity of gamma rays is proportional to the intensity of the cosmic rays J_{cr}. Therefore, when measuring the flux F_γ from some source containing a gas (molecular cloud, the galaxy), we obtain information on J_{cr}. Specifically, the flux $F_\gamma(>E_\gamma)$ of gamma rays with an energy greater than E_γ from a distant discrete source situated at a distance R is equal to (for details see Ref. 20, Ch. 18)

$$F_\gamma(>E_\gamma) = \frac{\overline{(\sigma J_{cr})} N(V)}{R^2}, \quad (4)$$

where

$$\bar{q}_\gamma = \overline{(\sigma J_{cr})} = \int_{E_\gamma}^{\infty} \sigma(E_\gamma,\ E) J_{cr}(E) \mathrm{d}E,$$

$\sigma(E_\gamma, E)$ is the cross section for the formation of a gamma photon of energy E_γ from cosmic rays of energy E, and $N(V)$ is the total number of particles (nuclei) of the gas in the source. From gamma-astronomical data for cosmic rays in the Galaxy we have

$$\bar{q}_{\gamma,G} = \overline{(\sigma J_{cr,G})} \approx 2 \cdot 10^{-26} \frac{1}{\text{s} \cdot \text{sr}}, \quad (5)$$

although in the literature somewhat different values are also encountered.[20] In Ref. 16 we assumed that $\bar{q}_{\gamma,G} = 1 \cdot 10^{-26}$. If the metagalactic model is valid, then in a steady-state picture one must assume that in the Magellanic Clouds we have $J_{cr} = J_{cr,G}$ and thus we can predict the value of $F_\gamma(>E_\gamma)$ for the large Magellanic Cloud (LMC) and for the small Magellanic Cloud (SMC). According to the calculations of Ref. 16 (with doubling the value of $\bar{q}_{\gamma,G}$) we obtain

$$F_{\gamma,LMC}(E_g > 100\ \text{MeV}) \approx 4 \cdot 10^{-7}\ \text{photons/cm}^2\text{s}, \quad (6a)$$

$$F_{\gamma,SMC}(E_\gamma > 100\ \text{MeV}) \approx 2 \cdot 10^{-7}\ \text{photons/cm}^2\text{s}. \quad (6b)$$

In Ref. 21 somewhat different parameters have been taken for the LMC, specifically, $R = 52$ kpc, the mass of neutral hydrogen $M_{HI} = 5.1 \cdot 10^8 M_\odot$, the mass of H_2 molecules is taken to be equal to $M_{H_2} = 1.0 \cdot 10^8 M_\odot$ which gives the value (determined from a graph)

$$F_{\gamma,LMC}(E_\gamma > 100M) \approx 5.5 \cdot 10^{-7}\ \text{photons/cm}^2\text{s}. \quad (7)$$

(Apparently in Ref. 21 the value $\overline{q_{\gamma,G}} = 2 \cdot 10^{-26}$ 1/s · sr per atom has been used, but here confusion is possible, since in the literature one more frequently uses the notation $q_\gamma/4\pi$ instead of q_γ; in Ref. 21 it is stated that $q_\gamma/4\pi = 2 \cdot 10^{-26}$ atom^{-1} s^{-1}, but apparently, the dimensionality sr^{-1} has been omitted).

In Ref. 18 the value $F_{\gamma,\mathrm{LMC}}(E_\gamma > 100$ MeV$) = (2.1 \pm 0.4) \cdot 10^{-7}$ is given without any explanations. As one can understand from Ref. 21 such a value differs from (7) in view of the use of the quantity $\bar{q}_{\gamma,G} = 1.6 \cdot 10^{-26}$ and of a reduction (by a factor of 1/3) of the amount of gas in the LMC. According to the observations of Ref. 18

$$F_{\gamma,\mathrm{LMC}}(E_\gamma > 100 \text{ MeV}) = (1.9 \pm 0.4) \cdot 10^{-7} \text{ photons/cm}^2\text{s}. \tag{8}$$

The large Magellanic Cloud is an active galaxy, supernovae flare up in it. Therefore one should think that in LMC cosmic rays are certain to be generated. For this reason the possible contribution of the metagalactic component is less than (8). And the value itself of (8) even without this is already by a factor of 2–3 smaller than the flux (7).

A still more impressive situation exists in the case of SMC. According to the observations of Ref. 6:

$$F_{\gamma,\mathrm{SMC}}(E_\gamma > 100 \text{ MeV}) < 0.5 \cdot 10^{-7} \text{ photons/cm}^2\text{s}. \tag{9}$$

This is by at least a factor of 4 lower than the value of (6b) and by a factor of 5 lower than the calculated value quoted in Ref. 6,

$$F_{\gamma,\mathrm{SMC}}(E_\gamma > 100 \text{ MeV}) = (2.4 \pm 0.5) \cdot 10^{-7} \text{ photons/cm}^2\text{s}. \tag{10}$$

We mention the possibility of making more precise the comparison of calculations with observations by using the relationship[16]

$$\Delta = \frac{F_{\gamma,\mathrm{SMC}}(>E_\gamma)}{F_{\gamma,\mathrm{LMC}}(>E_\gamma)} = \frac{N_{\mathrm{SMC}}/R^2_{\mathrm{SMC}}}{N_{\mathrm{LMC}}/R^2_{\mathrm{LMC}}} = \frac{\Phi_{21}(\mathrm{SMC})}{\Phi_{21}(\mathrm{LMC})}. \tag{11}$$

Here it is assumed that in accordance with the metagalactic model the intensity of cosmic rays in the SMC and LMC are the same, while Φ_{21} are the observed fluxes of radio emission at a wave length of 21 cm. More accurately, the fluxes have to be corrected by taking into account the reabsorption in the clouds themselves. The corresponding data[22] lead to the value $\Delta = 0.85$ instead of the estimated values $\Delta = 0.56$ and $\Delta = 0.68$ given in Ref. 16. The errors in the determination of the fluxes Φ_{21} are such that the limiting values are respectively equal to 0.54 and 1.36. According to the data on gamma rays in accordance with (8) and (9) $\Delta < 0.25$–0.33 and thus the use of the relationship (11) also does not agree with the metagalactic model.

On the whole, all the results quoted above indicate that in the Magellanic Clouds the equality (2) does not hold and thereby the metagalactic model is not confirmed. The equality (2) could be violated under non-steady-state conditions. Specifically, if a strong wind is blowing out of the Cloud the cosmic rays will be partially "blown out" (V. S. Ptuskin brought this possibility to my attention.) In the case of the SMC which is considered to be in a non-steady state[6,23] such a possibility deserves analysis. However the LMC is in a steady state[24] and here there is no basis at all for the assumption of "blowing out." Naturally both the calculations and, possibly, also the observations will be made more accurate. According to the observations of GRO it will probably be possible to determine also the gradient of the intensity of cosmic rays in the Galaxy. But, I think, the metagalactic model can be regarded already now as reliably refuted.

Thereby the justification of the galactic model of the origin of cosmic rays adopted in Ref. 1 is completed. Forty years have elapsed! Of course during these years a lot has been done,[4,5] but on the whole we have an example of how long one sometimes has to wait in order to delete white spots from the physical picture.

A discussion of the problem of the origin of cosmic rays, its status, its prospects and the problems of development are not included in the aim of the present article (with regard to this see in particular Refs. 4 and 5). Nevertheless it is appropriate to make two concluding remarks with respect to the above. Starting with 1983 (Ref. 25) a number of communications appeared concerning the observations of gamma rays with an energy $E_\gamma > 10^{14}$–10^{15} eV from a number of sources and primarily from the source in Cygnus X-3 (see the review in Ref. 5, Ch. 7). These communications evoked some enthusiasm and the indication that the available data were not reliable were to some extent ignored. However more recent measurements (cf., for example, Refs. 26 and 27) do not confirm assertions about the presence of a noticeable gamma radiation with an energy of $E_\gamma > 10^{14}$ eV$=100$ TeV. In principle it is not excluded that earlier some kind of sporadic processes were observed, but, more likely, one was dealing with errors. At present ever larger installations are being constructed for the observation of EAS (extended atmospheric showers) with an area attaining a value of $5 \cdot 10^3$ km^2. With their aid the question of the flux of gamma rays with $E_\gamma > 10^{14}$ eV will evidently be clarified. But apparently one should not expect the kind of dramatism in this region which was foreseen and was reflected, for example, in Refs. 4 and 5.

The second remark concerns cosmic rays with an energy of $E > 10^{15}$–10^{16} eV. At $E \sim 3 \cdot 10^{15}$ eV a "break" is observed in the spectrum. In a reasonably good approximation we have the intensity $J_{\mathrm{cr}}(E < 3 \cdot 10^{15}) \propto E^{-2.7}$ and $J_{\mathrm{cr}}(E > 3 \cdot 10^{15}) \propto E^{-3}$ right up to the energy of $E \sim 10^{19}$ eV. Then the spectrum becomes less steep and continues without a break up to an energy of $E \sim 10^{20}$ eV. We note that there are extremely few particles with an energy greater than 10^{20} eV; according to Ref. 28 $J_{\mathrm{cr}}(E > 10^{20}$ eV$) = (3 \pm 2) \cdot 10^{-16}$ particles/m^2 s · sr which corresponds to the arrival of one particle per century on an area of 1 km^2 into a solid angle of 1 steradian.

What is the nature of the "break" and the origin of the cosmis rays beyond the "break," i.e., at $E \gtrsim 3 \cdot 10^{16}$ eV? This is the principal unclear fundamental question in the field of astrophysics of cosmic rays. Here both a galactic and a metagalactic origin is possible. Recently, for example, a model has been discussed in which all the cosmic rays beyond the "break" are formed in active galactic nuclei.[29] It is true that here one is dealing with protons while the chemical composition of the cosmic rays of ultrahigh energies is not clear. Some information about such cosmic rays and their possible sources is given in Ref. 5, Ch. 4. One can hope for significant progress in this field only with the construction of very large installations for recording the EAS in order to determine reliably the spectrum, chemical composition and anisotropy of the primary particles with ultrahigh energy. How much time will still be needed for this? Nevertheless one can hope that by the one-hundredth jubilee (by 2012) from the time of discovery of cosmic rays the problem will be essentially solved.

I take this opportunity to thank V. S. Ptuskin for his advice.

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Translated by G. Volkoff