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On the origin of cosmic rays

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The origin of the main part of the cosmic rays observed near the earth is discussed. This includes first of all the choice between galactic and metagalactic models and the source problem. Some remarks about other related topics also are made especially in connexion with the prospects for the future research.

1. Introduction

The problem of the cosmic-ray origin has been under discussion already for several decades (see, for example, Rosen 1969) and even the present author has been engaged in it, fortunately, among many other topics, for more than twenty years (the first detailed paper was Ginzburg 1953). Particularly, I have expressed a rather optimistic opinion as to the possibility of verifying the basic assumptions which underlie a definite galactic model of the cosmic-ray origin. It would not be out of place, therefore, to begin this article with the confession that the problem of the origin of the main part of the cosmic rays observed near the Earth is still unsolved. On the other hand, this question can be now considered as basic, and of great importance rather subjectively, say, from the anthropocentric point of view. In fact, our Galaxy belongs to the class of normal galaxies and its total cosmic-ray energy is $W_{\text{cr}} \approx 10^{48}\text{–}10^{49}$ J, while for the most powerful radiogalaxies, apparently, $W_{\text{cr}} \approx 10^{53}\text{–}10^{54}\,\text{J} = 10^{6}\text{–}10^{7}\,M_{\odot}c^2$. In general, one of the most important astronomical results of the last two decades is the establishment (on the basis of radioastronomical data) that cosmic rays are a universal and important cosmic phenomenon. Relativistic charged particles are effectively generated on the stars (particularly, on the Sun), in supernova flares, in the galactic nuclei and in quasars; and the cosmic-ray energy and pressure are sometimes so large that they are to a great extent responsible for the energetics and dynamics of some regions, for example, supernova remnants and radioemitting 'clouds' in radiogalaxies. It is just in this connexion that cosmic-ray astrophysics or, as it has lately been called, high energy astrophysics, arose as a special branch of astronomy. (Perhaps, these terms can be used simultaneously since only charged particles are called cosmic rays. Meanwhile high energy astrophysics includes also X-ray and γ-ray astronomy.)

The problem of the origin of cosmic rays observed near the Earth is in this respect only a specific case to which, however, the present report is devoted. There is every reason for this; it is only about cosmic rays near the Earth (or, more precisely within some parts of the Solar System) that we know such things as their chemical composition and the relative role of the proton–nuclear and electron–positron components. As to cosmic rays far from the Earth and particularly outside the Galaxy, almost all the data were obtained on the basis of a synchrotron interpretation of non-thermal cosmic radiation and some additional far reaching hypotheses which use the data on the cosmic rays near the Earth (see §3*b*). Therefore only the origin of cosmic rays observed near the Earth can be at present the object of a rather extensive

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well-grounded investigation. The fact that this question also has not yet been answered reliably of course, upsets and even somewhat irritates physicists. One should bear in mind, however, that the corresponding difficulties are first of all connected with the still remaining uncertainty concerning some fundamental astronomical data. It is sufficient to mention for example, the mean concentration of intergalactic gas n_{mg} which is at present estimated to be between the limits $n_{mg} \approx 10^{-7}$–$10^{-5}\,\mathrm{cm^{-3}}$ (density, $\rho \approx 10^{-31}$–$10^{-29}\,\mathrm{g\,cm^{-3}}$) in our epoch. If the value $n_{mg} \approx 10^{-5}\,\mathrm{cm^{-3}}$ were established, at least some of the metagalactic models of the cosmic-ray origin would be disproved. Thus, there is no particular reason to be surprised that the solution of such an astrophysical problem as the cosmic-ray origin has not yet been found in the sense that a quite reliable and definite foundation has not been established. It is in fact much more surprising that, in spite of extreme difficulties with obtaining information in extra-galactic astronomy and cosmology, this field is developing rather rapidly and dramatically.

There is no possibility, and probably no necessity, of continuing these general remarks and we shall turn to the discussion of the origin of the main part of the cosmic rays observed near the Earth (for brevity in what follows we shall refer to this simply as cosmic-ray origin). This means that we shall not touch upon cosmic rays of solar origin (see, for example, Dorman 1973). Besides, unless the opposite is mentioned, we shall not discuss cosmic rays of super-high energy which can be of a metagalactic origin even if the greater part of cosmic rays originate in the Galaxy.

2. Questions to be answered and main models

To solve the problem of the cosmic-ray origin at least in the first approximation means to answer the following questions.

1. What is the region around the Solar System in which cosmic rays are trapped?

Such a region hardly has a distinct boundary but in general we mean the region whose parameters characterizing cosmic rays are approximately the same as those near the Earth (of course, disregarding the Earth's magnetic field and the influence of the solar wind). In terms of the cosmic-ray energy density w_{cr} this means that in the trapping region

$$w_{cr} \approx w_G \approx 10^{-19}\,\mathrm{J\,cm^{-3}}. \tag{1}$$

2. What are the main cosmic-ray sources in the trapping region?
3. How do cosmic rays propagate in interstellar and intergalactic space?

A number of features of the chemical composition of cosmic rays and their high degree of isotropy should be explained here. In this connexion several not very clear theoretical problems arise such as the conditions of applicability of the diffusion approximation for the motion in cosmic magnetic fields, and the role of plasma effects particularly for cosmic-ray isotropy.

4. What are the acceleration mechanisms and other processes in cosmic-ray sources?

The importance of this problem is quite evident. At the same time within wide limits it can be separated from the others and, in particular, from the answer to question 2 about the nature of the main cosmic-ray sources. In other words the source problem can be divided into external and internal parts (like external and internal ballistics) and, specifically, it is possible to indicate the main source and some of their characteristics such as power and spectrum, even without analysing the processes in the sources themselves.

5. What are the answers to questions 1–4 applied to the electron–positron component?

The energy density and intensity of the cosmic-ray electron component (or, more precisely,

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the electron–positron component) are of the order of 1 % of those for the proton–nuclear component and when merely speaking of cosmic rays one means their proton–nuclear component. The electron component is however extremely important, at least with regard to the fact that this component is responsible for synchrotron cosmic radioemission. The trapping region and sources of the electron component are not at all obliged, at least logically, to coincide with the trapping region and sources of the proton–nuclear component. The same can be said about the propagation conditions and acceleration mechanisms. Just to stress this point we separate problem 5 from the other questions.

All the above mentioned questions are interconnected and, besides, we could point out some other problems, or formulate what has been said in a different manner. Owing to the evident subjectivity of almost any division or classification, it is hardly necessary to discuss this aspect in more detail.

TABLE 1. MODELS OF COSMIC-RAY ORIGIN

models		the trapping region (in this region $W_{cr} \approx W_G \approx 10^{-19}$ J/cm^3)	basic sources†
galactic models	models with halo	quasi-spherical halo with radius $R_h \approx 3$–5×10^{22} cm or flattened halo with $R_{max} \approx 5 \times 10^{22}$ cm and $R_{min} \approx 5 \times 10^{21}$ cm	supernovae (including cosmic-ray acceleration by pulsars), galactic nucleus (explosive or continuous activity of the nucleus); stars of different types (for example magnetic stars and, particularly, magnetic white dwarfs))
	disk models	disk (of the radio-disk type) with $R \approx 5 \times 10^{22}$ (Galaxy radius) and half-thickness $h_d \approx 1$–2×10^{21} cm	
metagalactic models	universal (quasihomogeneous) model	the whole metagalaxy (we mean, however, the region with red shift parameter $Z \lesssim 5$–100)	galaxies of different types (particularly, radiogalaxies and quasars)
	local models	a certain region of the metagalaxy surrounding the Galaxy (local group of galaxies, local or Virgo superclusters of galaxies, etc.)	

† We mention some possible sources discussed in literature but do not at all treat them as equal (specifically, in our opinion, the basic cosmic-ray sources in galactic models are supernova explosions and particularly cosmic-ray acceleration by pulsars arising from these explosions).

The most essential element on the way to answering the above-mentioned questions is the choice of the model of cosmic-ray origin (more often one speaks about 'theories' of cosmic-ray origin but the term theory is hardly suitable here). The main alternative is the choice between galactic and metagalactic models (as is already clear from the names, the question is whether cosmic rays observed near the Earth originate mainly in the Galaxy or outside it, i.e. in the metagalaxy). The second stage is the division of metagalactic models into a universal (or quasi-homogeneous) and a local one. Galactic models are first of all divided into those with halo or disk models (a summary of some main features of these four types of model is given in table 1). Many other models of an intermediate type such as a 'disk' model with $r_d \approx 10^{22}$ cm, which does not differ from a model with a flattened halo, and models with different trapping regions for protons and some nuclei could of course be suggested. It should also be emphasized that we consider all the models mentioned in table 1 to be quasi-stationary, i.e. their parameters change little during the time $T_G \gtrsim 10^9$ years (a). There are some reasons for this assumption, but it cannot be considered strictly proved (see, for example, Ginzburg 1969*a*; Van Loon

1973). There is much literature devoted to cosmic rays. The most recent complete data can be found in the conference papers of the 13th International Cosmic Ray Conference (Denver U.S.A., 1973). Here we mention only a few books and papers without any claim to the particular importance of our references. Nevertheless at this stage it seems reasonable to direct our attention only to the models presented in table 1. In any case we shall follow this course, but first we shall consider the character of the information on cosmic rays which can be obtained by different methods.

3. The sources of information about cosmic rays

(a) *The study of cosmic rays near the Earth*

The intensities, or spectra, $I_{Z,A}(E)$ of protons and nuclei (A is the mass number, Z is the atomic number) and the intensity of the electron–positron component $I_{e^\pm}(E)$ as a function of the total energy E of the corresponding particle can, in principle, be measured near the Earth. Taking into account the high degree of cosmic-ray isotropy, when determining the spectrum one can ignore any anisotropy. The degree of anisotropy $\delta = (I_{max}-I_{min})/(I_{max}+I_{min})$ can be measured separately. The influence of the Earth's magnetic field can be taken into account; at $E_K = E-Mc^2 \gtrsim 1$ GeV the distortion of the spectrum in the Solar System is not too large. Thus, in principle, one can obtain a relatively large amount of information on cosmic rays in the immediate neighbourhood of the Solar System. This is what we mean when speaking of cosmic rays near the Earth. This data can evidently be extrapolated quite reliably to a certain 'near-solar' region with dimensions of the order of 10–100 pc (cosmic-ray isotropy and the use of laws of charged particle motion in a magnetic field are essential here).

Unfortunately, in spite of long years of investigations the information about the functions $I_{Z,A}(E)$, $I_{e^\pm}(E)$ and $\delta_{Z,A,e^\pm}(E)$ is not complete in many respects, if present at all. Therefore, we often have to use only the spectrum $I_{cr}(E)$ for all cosmic rays, the spectrum $I_e(E)$ for the whole of the electron–positron component and so on.

In the framework of our report we shall restrict ourselves only to some part of the data, deliberately rounding off all the numbers. Thus we have already mentioned such an important parameter of cosmic rays as the energy density $w_{cr} = 4\pi(E_K/v)\,I_{cr}(E)\,dE$ (see (1)), where $E = Mc^2/(1-v^2/c^2)^{\frac{1}{2}} = Mc^2+E_K$. For a more accurate calculation the contribution from nuclei with different masses M should be summed up.

The data on the chemical composition of cosmic rays give a quite reliable estimate for the thickness of matter traversed by cosmic rays (only relativistic particles with $v \simeq c$ are considered).

$$x = c\rho\, T_{cr} \approx 5 \text{ g cm}^{-2}. \tag{2}$$

$\rho \simeq 2\times10^{-24}\, n$ is some average gas density with concentration n along the path of the cosmic rays and T_{cr} is an average time of travel, i.e. some characteristic lifetime for cosmic rays in the Galaxy (in the approximation in which x is the same for protons and other nuclei this time T_{cr} is the exit time of the cosmic rays from the trapping region). The result (2), generally depends rather weakly on the choice of the model if we disregard such models as the regular model corresponding to the 'slab'-approximation (Ginzburg & Syrovatskii 1964, 1971; Ptuskin 1972, 1973). According to (2), $T_{cr} \approx 10^{-10}/\rho$ and for the cosmic-ray propagation respectively in the disk ($n_d \approx 1$ cm^{-3}) and in a halo ($n_h \approx 10^{-2}$ cm^{-3})

$$T_{cr,\,d} \approx (1\text{–}3)\times10^6 \text{ a}, \quad T_{cr,\,h} \approx (1\text{–}3)\times10^8 \text{ a}. \tag{3}$$

The approximate nature and the conventional character of these estimates are evident. Besides, they are based on the assumption that the cosmic-ray sources themselves contribute very little to the value of x which is certainly not proved though quite probable (Silberberg, Shapiro & Tsao 1973). To find not the thickness x but the time T_{cr} (and in particular to choose the value of $T_{cr,d}$ or $T_{cr,h}$ if just these limiting cases reflect reality) one must have some 'clock'. Its role can be played by different radioactive nuclei (such as ^{10}Be, ^{53}Mn, ^{237}Np, ^{244}Pu, ^{247}Cm) with life time exceeding 10^6 a as well as by the energy spectrum of the positron component of cosmic rays. In the latter case we have in mind that relativistic positrons are very likely to be produced by the cosmic-ray proton–nuclear component as a result of collisions in the interstellar gas. Therefore, the positron generation spectrum is known and, say, in a rough approximation has the form $q_{e^+} = q_0 E^{-2.7}$. Then near the Earth the spectrum will be of the same form $I_{e^+}(E) = KE^{-2.7}$ only if the positron's 'age' T_{e^+} is much less than the characteristic time $T_{s,C}$ of their energy loss due to synchrotron and Compton losses (see §4; for simplicity we assume here also that the diffusion coefficient is energy independent). If $T_{e^+} \gg T_{s,C}$, in the above example $I_{e^+}(E) = KE^{-3.7}$. Unfortunately, the positron component spectrum has not yet been determined to the required accuracy. Out of the radioactive cosmic-ray nuclei, ^{10}Be is most interesting. Its half-life time $T_{\frac{1}{2}} \sim 1.5\times 10^6\, E/Mc^2$ a. Obviously, at $T_{cr} \gg T_{\frac{1}{2}}$ no nuclei of ^{10}Be should be observed in cosmic rays ('decay'). On the contrary, if $T_{cr} \ll T_{\frac{1}{2}}$ all ^{10}Be produced must be preserved ('survival'). To solve the problem one must reliably determine the isotopic composition of Be in cosmic rays (Raisbeck & Yiou 1973) which has not yet been done. Note also that quantitative determination of T_{cr} according to the appropriate data requires comparison with calculations for definite models, including diffusion ones, and already for this reason it will contain some unknown factor. The latter may be particularly large when we take into account some local features in the region near the Sun (this remark concerns still more the estimation of the degree of anisotropy δ). In this connexion the case of complete decay of ^{10}Be will confirm the halo model ($T_{cr,h} \gg 1$–3×10^6 a) but if the decay is partial or even non-existent it is very difficult to disprove this model and to prove that the disk model is correct (see also §5).

(b) *Radioastronomy*

The intensity of radioemission $J_\nu(b, l)$ as a function of frequency ν and galactic latitude and longitude b and l can be measured. Suppose then that radioemission is of a synchrotron nature or that the emission of another origin primarily thermal radiation connected with the interstellar gas is already separated. Then the intensity J_ν is expressed by some integral which depends on the intensity of the cosmic-ray electron component $I_e(E, \boldsymbol{r})$ and on the magnetic field project $H_\perp(\boldsymbol{r})$ perpendicular to the direction of observation; integration is taken over the coordinates $\boldsymbol{r}$ along the line of sight (see Ginzburg & Syrovatskii 1964, 1971; Ginzburg 1969*b*; Bulanov, Dogel & Syrovatskii 1972). If $I_e \approx E^{-\gamma}$, then $J_\nu \approx \nu^{-\alpha}$, $\alpha = \frac{1}{2}(\gamma-1)$; in this case it is also easy to connect the very values I_e and J_ν under an additional assumption that the functions I_e and $H_\perp$ are constant for a length L along the line of sight and farther away $I_e = 0$. No one of these assumptions is real, however, when applied to the total galactic radioemission. It is enough to say that the radioemission spectrum is not power like, i.e. when the power approximation is used, $\alpha = \alpha(\nu)$. Therefore the only way to solve the radio-halo problem in the Galaxy and, generally, to find the electron component distribution in the Galaxy, is to carry out rather cumbersome calculations which connect the observable quantity $J_\nu(b, l)$ with the unknown quantity $I_e(E, \boldsymbol{r})$ without neglecting its $\boldsymbol{r}$-dependence. One must assume also the value of the field $H_\perp(\boldsymbol{r})$, but on the other hand it is possible, and necessary to use the data on the intensity $I_e(E)$ near the Earth. This program was carried out by Bulanov *et al.* (1972) and led to the conclusion that a quasispherical radio-halo exists with $R \approx 10$ kpc and that the lifetime of relativistic electrons

$$T_e \approx R^2/2D \sim 2\times10^8 \text{ a}, \qquad (4)$$

where D is the diffusion coefficient. In the original paper (Bulanov *et al.* 1972) and in the report by Ginzburg & Syrovatskii (1971) the value $T_e \sim 2\times10^7$ a is presented and the halo is considered to be flattened with half-thickness $R_{min} \approx 1$ kpc. Bulanov *et al.* have found, however, an error in their computer calculations and the value (4) corresponds to their correct result (to be published).

Some uncertainties in the account taken of the metagalactic component and in the contribution from inhomogeneities in the radio-disk as well as uncertainty in the value of the intensity J_ν and the necessity to make assumptions concerning the magnitude of the field H for equivalent assumptions make the result (4) preliminary. Thus we are far from stating that the existence of a pronounced radio-halo in the Galaxy is proved. We do state, however, that the only known attempt to analyse this problem in a somewhat consistent and correct manner testifies to the existence of a radio-halo and even of a rather pronounced quasi-spherical radio-halo. In our opinion all the data available, including the recent ones (Baldwin & Pooley 1973), do not contradict a similar conclusion concerning all or at least part of other spiral galaxies similar to ours. One should only bear in mind that when moving away from the galactic plane both the intensity $I_e(E)$ at $E > 1$–10 GeV and, most probably, the field H decrease considerably. Therefore an extensive halo can be noticeable only at long wavelengths (apparently at $\nu < 100$–200 MHz) but in this case there is also no reason to expect a high intensity. For our Galaxy at $\nu = 180$ MHz a brightness temperature even for a 'strong' radio-halo is lower than 80–100 K; for more details see Ginzburg (1970).

In principle, a fundamental limitation connected with the use of radioastronomical data for obtaining information on the cosmic-ray electron component is the necessity of setting the magnetic field H in the radiating region from independent considerations. (In fact, measurements of radioemission polarization present some valuable information on the field H and, in particular, on its configuration but this does not affect the aspect presented here. Besides, if we use the data on the electron component near the Earth and assume the dimensions of the region filled with these relativistic electrons one can estimate the field H.)

It is true that for the power law spectrum $\alpha = \frac{1}{2}(\gamma-1)$ independent of the field strength. Besides, irrespective of the magnitude of H or $H_\perp$, only assuming the approximate constancy of average values of these quantities in space, one can within some limits judge the space dependence of the intensity $I_e(E, \boldsymbol{r})$. In this way one may conclude that the 'near-solar' region ($R \approx 10$–100 pc) is not something exclusive and, thus, the data on cosmic rays near the Earth, or, strictly speaking, the data on their electron component, can to the first approximation be extended at least to a galactic radio-disk of radius $R \approx 10$–15 kpc and thickness $2h_d \approx 800$ pc. In general, however, as has been said, a radio-astronomical determination of the intensity I_e and energy density $w_e = (4\pi/c)\int EI_e(E)\,dE$ requires that the field H be determined independently. The same concerns the transition from the electron component to all cosmic rays. In terms of the energy density (or the total energy) one usually assumes (see, for example, Ginzburg 1969*a*)

$$w_{cr} = \kappa_r w_e = \kappa_H^{-1} H^2/8\pi, \qquad (5)$$

i.e. two coefficients $\kappa_r = w_{cr}/w_e$ and $\kappa_H w_m/w_{cr} = H^2/(8\pi w_{cr})$ are introduced (it would be, probably, more convenient to introduce coefficients κ_r^{-1} and κ_H but we follow the more usual definition).

Near the Earth $$\kappa_r \approx 100, \quad \kappa_H \approx 1. \tag{6}$$

More precisely, the value of κ_r is measured directly and the estimate $\kappa_H \approx 1$ follows from (1) and independent estimates of the galactic magnetic field intensity $H_G \approx 4 \times 10^{-4}$ A/m (5×10^{-6} Oe). At the same time the value $\kappa_H = 1$ corresponds to equipartition of energy with respect to 'degrees of freedom', which in some cases (under quasi-stationary conditions) can be expected from rather general considerations. It is quite evident, however, that the estimates (6) are not a law of Nature. In the regions with great energy losses for electrons (specifically, one can think about synchrotron and Compton losses) the values $\kappa_r \gg 10^2$ are quite possible and even probable. On the other hand where electrons are preferentially accelerated, evidently $\kappa_r \ll 10^2$. Further under nonstationary conditions, for example, when cosmic-ray generation results from an explosion in a region with a comparatively weak field, it is likely that $\kappa_H \ll 1$. On the contrary, in the regions with a strong magnetic field, for example, near pulsars, magnetic stars and near the Earth $\kappa_H \gg 1$.

So, generally, the lack of knowledge of the coefficients κ_r and κ_H is the weakest point in cosmic-ray astrophysics based on radio-astronomical data.

(*c*) *X-ray astronomy*

While synchrotron radioemission is generated by the motion of relativistic electrons in a magnetic field, some fraction of X-ray radiation is produced by the same electrons being scattered on photons, in particular, by radiophotons of the relict thermal radiation with a temperature 2.7 K. In the latter case and in some other cases the data on radiation in the X-ray generation region can be considered to be known, as the measurements of the X-ray intensity make it possible to find the generating component intensity $I_e(E)$, and then w_e. Comparing such X-ray data with radio data for the same region of the source one can, in principle, find the field H in this region. Unfortunately, this method has not yet been fruitful because of the difficulty in separating the Compton component of X-ray radiation and because of the lack of corresponding X-ray data (spectral measurements of high sensitivity are needed). But even if the field H is known (it can, in principle, be measured or estimated by a number of methods) and, therefore, the density w_e can be considered known (radio method), or this density is determined irrespective of the values of the field H (X-ray method), we cannot yet find the energy density of all cosmic rays w_{cr}. It is just the lack of knowledge of the density w_{cr} far from the Earth and particularly in halo and in the intergalactic space that is the source of the fundamental uncertainty in the choice between different models of the cosmic-ray origin.

(*d*) *Gamma-astronomy*

The pressure of isotropic relativistic cosmic rays $p_{cr} = \frac{1}{3}w_{cr}$ is, generally speaking rather substantial. Thus, there arises the possibility of estimating w_{cr} by dynamic effects in the intergalactic and interstellar gas. This way is, however, indirect and for some reasons it is not very promising. The only direct and rather universal way of determining the intensity of the cosmic-ray proton–nuclear component $I_{cr}(E)$ or, at the first stage, at least the energy density w_{cr} far from the Earth is the γ-astronomical method. The point is that, when colliding in a gas, relativistic protons and nuclei produce various particles which finally decay emitting γ-photons.

A fundamental role here is played by a direct-production of π^0 mesons but γ-photons are also produced under the decay of Σ^0-hyperons and secondary π^0-mesons from such processes as $K^{\pm} \rightarrow \pi^{\pm} + \pi^0$, $\Lambda \rightarrow n + \pi^0$ and some others. Thus, the γ-ray intensity $I_\gamma\,(E_\gamma)$ is determined by the product of $I_{cr}(E)$ and the gas concentration n along the line of sight.

This way of determining I_{cr} has been known for more than ten years, but only after the first γ-astronomical measurements were carried out (Kraushaar *et al.* 1972) has it attracted great attention (Stecker 1971; Ginzburg 1972; Stecker & Trombka 1973). We shall restrict ourselves both for illustration and further presentation to one example, namely, we shall consider a certain 'discrete' γ-ray sources which is at the distance R from us and find the corresponding γ-ray flux $F_\gamma\,(>E_\gamma)$ for energy higher than E_γ

$$F_\gamma\,(>E_\gamma) = \int_\Omega I_\gamma\,(>E_\gamma)\,\mathrm{d}\Omega = (\sigma I_{cr})\,N(V)/R^2$$
$$\simeq 5\times 10^{23}(\sigma I_{cr})\,M/R^2 \quad \text{photons cm}^{-2}\,\text{s}^{-1}. \tag{7}$$

Here $I_\gamma(>E_\gamma)$ is the integral intensity of γ-rays, Ω is a solid angle at which the source is seen, $N(V) = nV$ is the number of nuclei in the source of volume V and mean concentration n, $M \simeq 2\times 10^{-24}\,N$ is the gas mass in the source (the chemical composition of the gas is considered to correspond to the mean distribution of the elements) and, finally

$$(\sigma I_{cr}) = \int_E^\infty \int_{E=E_\gamma}^\infty \sigma(E, E_\gamma) I_{cr}(E)\,\mathrm{d}E\,\mathrm{d}E_\gamma,$$

σ being the corresponding cross-section for γ-ray formation under the action of cosmic rays with intensity $I_{cr}(E)$. For galactic cosmic rays $I_{cr}(E) = I_G(E)$ and for example the value $(\sigma I_\gamma)_{E_\gamma=100\,\text{MeV}} \simeq 10^{-26}\,\text{s}^{-1}\,\text{sr}^{-1}$ and

$$F_\gamma\,(>100\ \text{MeV}) \simeq 5\times 10^{-3} M(w_{cr}/w_G)/R^2 \quad \text{photons cm}^{-2}\,\text{s}^{-1}, \tag{8}$$

where R is in cm, mass M in grams and w_{cr}/w_G is the ratio of the cosmic-ray energy density in the source to that near the Earth (under the assumption that the energy spectra are the same in both cases).

The measurement of the flux $F_\gamma\,(>100\ \text{MeV})$ for a source which is at a known distance and contains a known amount of gas allows us, obviously, to find immediately the cosmic-ray energy density in the source w_{cr}. In the cases where the gas is basically neutral hydrogen (this is true for the Magellanic Clouds; see §6) the ratio $M/R^2 \simeq 1.2.M_{HI}/R^2$ is measured directly by the hydrogen line ($\lambda = 21$ cm) intensity. The assumption concerning the similarity of the cosmic-ray spectra in the source and near the Earth is sometimes justified and in some cases does not lead to a great error. One, however, must be sure that one deals with γ-rays of 'nuclear' origin (formation and decay of π^0-mesons, etc.) but a clear answer to this question can be given by spectral measurements. In the simplest case at least the ratio

$$(F_\gamma\,(>50\ \text{MeV}) - F_\gamma\,(>100\ \text{MeV}))/F_\gamma\,(>100\ \text{MeV})$$

should be known. For 'nuclear' γ-rays it is equal to 0.12 whereas in other cases it is much larger (see Fichtel, Hartman, Kniffen & Sommer 1972).

Thus, γ-astronomical measurements, and practically they alone, can eliminate the fundamental uncertainty existing in cosmic-ray astrophysics since they make it possible to find directly the density w_{cr} far from the Earth without introducing the coefficients κ_r or κ_H.

4. The origin of the cosmic-ray electron component

After the discovery in 1965 of the relict thermal radiation with a temperature of 2.7 K and, therefore, an energy density $w_{ph} = 4 \times 10^{-20}$ J cm^{-3}, it became finally clear that the cosmic-ray electron component is of galactic origin. In fact, the energy of a relativistic particle of charge e and mass m which travel in a magnetic field H and in a classical radiation field with the energy density w_{ph} changes according to the law

$$E(t) = E_0/(1+\beta E_0 t), \quad \beta = 32\pi e^4(w_{ph}+H^2/8\pi)/(9m^4c^7). \tag{9}$$

Hence, irrespective of the initial energy E_0 after a time $t = T_e$ the particle cannot have an energy higher than

$$E_{max}(T_e) = 1/(\beta T_e) = 1.56 \times 10^6/(T_e(w_{ph}+H^2/8\pi)) \text{ eV}, \tag{10}$$

where, as in (9), the radiation field and magnetic field are considered to be isotropic (on the average) and the numerical value is presented for electrons (or positrons), T_e is measured in seconds and the energy density in J cm^{-3}.

Even for rectilinear motion with a velocity $v \simeq c$ the observed electron of energy E eV could not be produced at a distance larger than

$$R_{max} = cT_e = 4.7 \times 10^{16}/((w_{ph}+H^2/8\pi)E) \text{ cm} \simeq 7 \times 10^{35}/E \text{ cm}, \tag{11}$$

where the latter value pertains to the metagalactic space with $w_{ph}+H^2/8\pi \simeq w_{ph} \simeq 4 \times 10^{-20}$ J cm^{-3}. In fact, the distance (11) to the source is greatly overestimated if we take into account that the trajectory is not a straight line and that additional energy losses within the Galaxy take place. We mean that in the Galaxy with the contribution from the magnetic field and optical radiation subject to the coordinates (disk, halo etc.) $W_{ph}+H^2/8\pi \approx (1\text{–}2)\text{–}10^{-19}$ J cm^{-3}. From this it follows that an electron when travelling in the Galaxy (say, from its boundaries to the Earth) during the time $T_e > 10^7$ a when near the Earth cannot have an energy higher than $E \approx 3 \times 10^{10}$ eV. At the same time the observed electron spectrum near the Earth does not cut-off at energies $E \approx 3 \times 10^{11}$ eV and, may be, still higher. Further, an electron of energy $E \approx 3 \times 10^{10}$ eV at the Earth would have an energy $E \approx 10^{11}$ eV near the Galaxy boundaries (at $T_e \sim 10^7$ a) and, according to (11) it could not come from a distance greater than 2 Mpc (with the account taken of the curvature of the trajectory, this maximum distance will probably decrease considerably). Meanwhile even the nearest radiogalaxy, Centaurus A, is at the distance $R \simeq 4$ Mpc.

Thus, electrons with energy $E > 1\text{–}3 \times 10^{10}$ eV are certainly of galactic origin and it is most improbable that the situation could change in the energy range $E > 10^9$ eV, and probably, lower energies.

The total intensity of galactic radioemission is about 3×10^{31} J s^{-1}. Compton energy losses are apparently 2–3 times larger and thus the electrons in the Galaxy should be accelerated at the rate

$$U_e \sim 10^{32} \text{ J s}^{-1}. \tag{12}$$

For the characteristic lifetime $T_e \sim 10^7\text{–}10^8$ a we then obtain the total energy of the electronic component in the Galaxy

$$W_e \approx U_e T_e \approx 3 \times 10^{46}\text{–}3 \times 10^{47} \text{ J}. \tag{13}$$

The energy density of the electronic component near the Earth $w_e \approx 10^{-2} w_{er} \sim 10^{-21}\,\mathrm{J\,cm^{-3}}$ and, hence, the characteristic 'trapping' volume

$$V_e \approx W_e/w_e \approx 10^{67}\text{–}10^{68}\,\mathrm{cm^3}, \tag{14}$$

where we have discarded the factor of order 3 due to a rather probable decrease of the density w_e at the boundaries of the trapping region (however one should mention that the factor of order 3 is, strictly speaking, outside the accuracy of our estimates). The volume $V_h \approx 10^{68}\,\mathrm{cm^3}$ corresponds to a spherical region of the radius $R \approx 3 \times 10^{22}$ cm or to the quasispherical region with characteristic dimensions $R_h \approx (1\text{–}5) \times 10^{22}$ cm. We are thus dealing with a radio-halo. The volume $V_d \approx 10^{67}\,\mathrm{cm^3}$ corresponds to the disk with radius $R \approx 5 \times 10^{22}$ cm and half-thickness $h_d \sim 10^{21}$ cm, which just corresponds to the galactic radio-disk. As has been emphasized in §3 the problem of the existence of a pronounced radio-halo is not yet solved, though there are quite real possibilities in this respect. The point, apparently, is that the attention of radio-astronomers is fixed on the solution of problems which are at first glance more spectacular and which pertain to a high-frequency region. One should also bear in mind that the synchrotron radiation intensity decreases with the decrease of the magnetic field (by the law $H^{\frac{1}{2}(\gamma+1)}$ for the spectrum $I_e = KE^{-\gamma}$). Therefore not a sharp decrease of electronic concentration but a corresponding decrease of a magnetic field strength can account for the absence of a substantial radioemission from the regions with a height above the galactic plane $Z > h_d \simeq 400$ pc $\approx 10^{21}$ cm. In other words, the absence of radio-halo would not yet testify to the absence of a physical halo or a cosmic-ray halo (see Ginzburg 1967, 1969*a*; Ginzburg & Syrovatskii 1971).

Relativistic electrons are certainly present in supernova remnants, their total energy per remnant reaching 10^{41} J and even higher values. At a frequency of supernova flares in the Galaxy $1/\tau_{sn} \sim 1/30$ to $1/50\,\mathrm{a^{-1}}$ we see that supernovae can quite well generate the cosmic-ray electron component with the power (12). Such a conclusion is especially true because part of relativistic particles could have left the envelopes at the previous stages of their evolution and, besides, pulsars exhibit their activity longer than the remnants are seen. On the other hand, the presence of relativistic electrons in the remnants does not guarantee their output to the interstellar space with a sufficient power and other parameters. Thus, there is no adequate safeguard that the basic source of the cosmic-ray electron component in the Galaxy is supernovae (including pulsars), it is only most probable. Note that the region of the galactic centre is not a suitable candidate at least for electrons with energy $E > 1\text{–}3 \times 10^{10}$ eV because of the great energy losses on the way from the centre to the Sun for the time $T_e > 10^7$ a or, irrespective of the time of propagation, if the particle acceleration in the central region took place 10^7 a ago at the last considerable explosion of the galactic nucleus. In addition to supernovae, novae and magnetic stars, for example, could play some role. However they hardly can compete with supernovae and pulsars as to effectiveness in particle acceleration, particularly if their energy is high.

Thus we may state that as to the cosmic-ray electron component, there is no fundamental uncertainty in the choice of the type of model. And so instead of discussing the basic problem, we can in this case direct our attention to quantitative questions.

5. On galactic models of the origin of the cosmic-ray proton–nuclear component

In the case of the proton–nuclear component uncertainties remain just in the foundation itself since, as we agree, metagalactic models have not been disproved quite rigorously and they are considered by some authors to be quite probable and viable (Brecher & Burbidge 1972). In such a situation, whether we want it or not, we must once again pay special attention to a comparison of galactic and metagalactic models.

In a galactic model with a quasi-spherical halo, and in a galactic disk model, cosmic rays take up volumes $V_h \approx 10^{68}$ cm^3 and $V_d \approx 10^{67}$ cm^3, respectively (see table 1), which corresponds to a total energy $W_{cr} \sim w_{cr} V = w_G V$ (see (1))

$$W_{cr,\,h} \approx 10^{49}\,\text{J}, \quad W_{cr,\,d} \approx 10^{48}\,\text{J}. \tag{15}$$

The energy W_{cr}, being divided into the typical lifetime (3), gives the power of the cosmic-ray sources

$$U_{cr} \approx (1\text{–}3) \times 10^{33}\,\text{J s}^{-1}. \tag{16}$$

The value spread is reduced three times since within the accuracy of the estimates (3) and (15) it is more correct to find U from the relations $U_{cr} \approx W_{cr}/T_{cr} \approx w_G Vc\rho/x \approx cw_G M/x$, where $M = \rho V \approx 5 \times 10^{42}$ g is the total gas mass in the Galaxy and x is the overall gas thickness (2). From this with $x \approx 5$ g cm^{-2} and $w_G \sim 10^{-19}$ J cm^{-3} we get the power $U_{cr} \sim 3 \times 10^{33}$ J s^{-1}, the same for both the models in their simplest form; for more perfect diffusion models the power U_{cr} already depends on the trapping region dimensions which is also reflected in (16), although the value spread can appear to be somewhat greater.

If the existence of a radio-halo is proved, it will be extremely difficult to have doubts as to the existence of a 'cosmic-ray halo' with a volume $V_h \approx 10^{68}$ cm^3 or somewhat greater. On the other hand the absence of a pronounced radio-halo does not yet prove that the proton–nuclear component of cosmic rays is localized in the radio-disk. Unfortunately, an analogous asymmetry in the proof or disproof concerns also the use of the ages of cosmic rays near the Earth $T_{cr,\,r}$ and T_{e^+} which can be determined from the amount of radioactive isotopes or from the positron spectrum (see §3*a*). In fact, if the values of $T_{cr,\,r}$ or T_{e^+} are high ($T_{cr,\,h} > 10^8$ a), this will prove the halo model (at least if we do not touch upon metagalactic models). If, on the other hand, the values of $T_{cr,\,r}$ and T_{e^+} are low ($T_{cr,\,d} < 3 \times 10^6$ a), the absence of a cosmic-ray halo is not yet proved. In this case one can state only that cosmic rays come to the Earth from a comparatively small region. This does not contradict the disk model but may as well be explained by the absence of a sufficient mixing of cosmic rays between the disk and the halo or even between a part of the disk close to the Sun and other regions of the Galaxy. Such a conclusion would certainly be rather radical and essential but it is compatible, for example, with the existence of a radio-halo, to say nothing of a cosmic-ray halo. There is no need to go on enumerating various possibilities and versions: first of all one has to estimate $T_{cr,\,r}$ and T_{e^+}.

As far as we know there are no real data at present testifying against a galactic model with a halo with good cosmic-ray mixing. One should also remember that the halo may prove not to be quasi-spherical but flattened (see table 1) and then it is not easily distinguished from a radio-disk with the usual thickness of about 1 kpc. A high degree of cosmic-ray isotropy is more natural for a model with a halo than for a disk model (see, however, Ptuskin 1973). Occupation by cosmic rays of a more 'swollen', halo, region rather than a flat, disk, region is also natural from dynamical considerations, taking into account that the cosmic-ray pressure in the disk $P_{cr} = W_{cr}/3 \approx 3 \times 10^{-14}$ Pa is rather great.

Supernovae, including pulsars, may well turn out to be the main cosmic-ray sources with the power (16). In fact, the average energy output at a supernova explosion W_{sn} is estimated to be no less than 10^{43}–10^{44} J and, therefore, the power $U_{sn} \approx W_{sn}/\tau_{sn} \gtrsim 10^{34}$–$10^{35}$ J s^{-1}. Hence, cosmic rays with the input power (16) can also be generated. More convincing is the fact that powers (16) and (12) for the generation of all cosmic rays and their electron component differ by 10–30 times only. The possibility of the electron component generation predominantly in supernovae is partly confirmed by radio-astronomical data. Thus it is sufficient, in practice, to assume that protons and nuclei acquire from pulsars and supernovae an energy only about 30 times greater than electrons. The following considerations testify to such an assumption: the analysis of a number of acceleration mechanisms, the data on particle acceleration of the Sun (it is for the most part the proton–nuclear component that reaches the Earth), and the presence of additional energy losses for electrons. The last is important because the power U_e was estimated as the ratio $U_e \approx W_e/\tau_{sn}$ where $W_e \approx 10^{41}$ J is the mean relativistic electron energy in the remnant. With the losses the acceleration mechanism must exceed this value. In the Crab nebula (which, however, is an exception) the electron component has already acquired no less than 10^{42} J by the present time. Finally considerations connected with their chemical composition (Arnett & Schramm 1973) lead to supernovae being suitable as cosmic-ray sources.

All this does not definitely prove that sources other than supernovae are not the main providers of cosmic rays. Such sources as the galactic nucleus are also of interest (the data of γ-astronomy are particularly important here, see Ginzburg 1972); a rather effective acceleration of cosmic rays with energy $E > 10^{10}$ eV near stars of different types, including magnetic stars but not pulsars, seems less probable.

There is no doubt that in the studies of the cosmic-ray origin there are many uncertainties and unclear questions. We have to restrict ourselves only to mentioning some of them. The mechanisms of diffusion, or pseudodiffusion, and for making cosmic rays isotropic in cosmic magnetic fields both in general and in a number of concrete regions (spiral arms, disk, halo, supernova remnants) are far from being clarified. These questions are, however, widely investigated and there is obvious progress in this field including the energy dependence of the diffusion coefficient (see, for example, Ginzburg, Ptuskin & Tsytovich 1973; Earl 1973; Ptuskin 1974; Bulanov & Dogel 1974; and the literature cited in these papers). The magnetic field configuration in the halo, and in general, in the transition region from the Galaxy to intergalactic space is unclear (see also §6). The discovery of pulsars gave rise to the study of particle acceleration mechanisms by rotating magnetic stars but there are many open questions here, even in application to the most investigated case, the Crab Nebula (Felten 1973). The region of super-high energies in which there are also many unsolved problems but which at the same time offers some very interesting possibilities requires special consideration (see Syrovatskii 1971; Sreekantan 1972; Osborne, Roberts & Wolfendale 1973; Stecker 1973).

How should we treat the impossibility, at the present moment, of choosing between different galactic models and the presence of various uncertainties in the attempts to develop these models qualitatively?

In our opinion all this makes us take care and seek different ways of verifying all suggestions but it cannot in the least testify against galactic and in favour of metagalactic models. We have tried, with the aid of the previous presentation, to confirm this. Now we shall restrict ourselves to only one very simple but rather convincing argument connected with the origin of the cosmic-ray electron component. In this case the galactic origin is proved (§4) and nobody denies this though it leaves many uncertain points. A precise model for the origin of the electron component cannot be constructed now but can be chosen at a later time. If we suppose in this model that the electron sources accelerate the proton–nuclear component also with an intensity 10–30 times higher than that for electrons, as is quite possible and natural on the basis of all available information and estimates concerning particle acceleration, we arrive at a galactic model of the origin of all cosmic rays which meets energetic requirements. It is also free of all possible 'difficulties' that are mutual for electrons, protons and nuclei. Only difficulties that are specific to the proton–nuclear component remain (e.g. chemical composition). These could, in principle, be regarded as actual 'difficulties' at the next stage only, when we deal with details and with quantitative analysis.

This position differs essentially from that of Brecher & Burbidge (1972) who have concluded that a metagalactic model of the 'origin for the bulk of the locally observed cosmic-ray nuclei is consistent with all current observations and, in contrast to galactic theories, offers a natural explanation for both their spectral shape at high energies and their isotropy'. In this situation we shall have to go back to (see Ginzburg 1969*a*; Ginzburg & Syrovatskii 1964, 1971) metagalactic models of the cosmic-ray origin.

6. On metagalactic models of the cosmic-ray origin

It is assumed in metagalactic models that in a very large part of the metagalaxy or at least in some metagalactic region near the Galaxy (see table 1) there are so many cosmic rays that their energy density is

$$w_{\mathrm{mg}} \sim w_{\mathrm{G}} \sim 10^{-19}\,\mathrm{J\,cm^{-3}} \tag{17}$$

and flowing into Galaxy they form the main part of the proton–nuclear component.

The mass density in galaxies, or, more exactly, in visible matter, is on the average $\rho_{\mathrm{mg}} \approx 3\times10^{-31}\,\mathrm{g\,cm^{-3}}$ and, therefore, $w_{\mathrm{mg}} \approx 10^{-19}\,\mathrm{J\,cm^{-3}} \sim 3\times10^{-3}\,\rho_{\mathrm{mg}}\,c^2$. (As will be clear from what follows a possible use of a three times larger value does not change the situation; the same can be said of the possibility of increasing ρ_{mg} in operation to the local, or so called Virgo, supercluster.) Such a cosmic-ray density in the metagalaxy corresponds to a colossal energy and it is a far reaching and unconfirmed, though logically possible, hypothesis that cosmic rays can acquire this energy.

Gravitational energy released under star formation seems to be the most powerful energy source for particle acceleration. But for the Sun this energy is of the order of $GM_{\odot}^2/r_{\odot} \approx 3\times10^{41}\,\mathrm{J} \approx 3\times10^{-6}\,M_{\odot}c^2$ and for other stars, including neutron stars, the picture does not change qualitatively. In supernova explosions nuclear energy is released but cosmic rays do not acquire more than $10^{43}\,\mathrm{J}$ per flare, which also corresponds to an energy of order $10^{-5}\,Mc^2$ if the mass of the original star $M \approx 10\,M_{\odot}$. If we start from radio-astronomical data and use values of the type (6), then in explosions of galactic nuclei with the formation of radiogalaxies energy output into cosmic rays does not exceed 10^{53}–$10^{54}\,\mathrm{J}$ which is $\lesssim 10^{7}\,M_{\odot}c^2$ or $10^{-5}\,Mc^2$, where $M \sim 10^{12}\,M_{\odot}$ is the mass of a powerful radiogalaxy. There are rather few such objects and therefore even varying the coefficients κ_r and κ_H one can hardly suppose that a mass larger than $10^{-5}\,Mc^2$ will be processed into cosmic rays. When determined by radio-astronomical data, cosmic-ray energy in the source $W_{\rm cr}$ is proportional to $\kappa_H^{-\frac{3}{7}}\,\kappa_r^{\frac{4}{7}}$ (see, for example, Ginzburg 1969*a*). Therefore, for example, even at $\kappa_H \approx 0.1$ and $\kappa_r \approx 1000$ the energy $W_{\rm cr}$ increases only by one order of magnitude in comparison with that obtained at $\kappa_H \approx 1$ and $\kappa_r \approx 100$. In collapse, as a final stage of long evolution of massive stars and galactic nuclei, including quasars, cosmic rays can acquire up to 0.1 Mc^2, though this is not proved. But the question arises about the fraction of mass in the Universe which has already collapsed. There are still no indications that this fraction is considerable and can amount to 10% of the total mass as is necessary for obtaining metagalactic cosmic rays with the energy density (17).

Thus both energetic considerations connected with the energy supply and direct calculations of energy output in different galaxies and quasars give no reason to believe that cosmic rays acquire energy corresponding to more than 10^{-4}–$10^{-5}\,\rho_{\rm mg}c^2 \sim 3\times10^{-21}$–$3\times10^{-22}$ J cm^{-3}. Therefore, a 30–300 times increase of this estimate which is necessary for obtaining relation (17) seems to us at least a very far reaching hypothesis and there are no real data to confirm it (particularly, in the paper by Brecher & Burbidge 1972).

At the same time, the above statement is not enough, of course, to disprove the possibility of reaching the energy density (17). Therefore, one has to think how we can disprove metagalactic models without touching upon the above mentioned arguments. We see three ways here.

First, the energy density $w_{\rm mg} \sim 10^{-19}$ J cm^{-3} and the corresponding pressure $P_{\rm mg} \sim 3\times10^{-14}$ Pa are much higher than the energy density $\frac{3}{2}Kn_{\rm mg}\,T_{\rm mg}$ and the pressure $Kn_{\rm mg}\,T_{\rm mg}$ of the metagalactic gas even at $n_{\rm mg} \sim 10^{-5}$ cm^{-3} and a temperature $T_{\rm mg} \approx 10^6$–10^7 K. Thus, the presence of cosmic rays with the energy density (17) in the intergalactic space should influence such phenomena as the expansion of radio-emitting clouds in radiogalaxies. Unfortunately, the present author does not know whether this question has been investigated and what possibilities offer themselves.

Secondly, penetration of metagalactic cosmic rays into Galaxy is possible only if the galactic magnetic field is 'open' enough. According to Parker (1973) it is rather difficult to meet this requirement and this author concludes that to provide the necessary cosmic-ray penetration into the Galaxy from outside required for metagalactic models is possible only if a new and unknown mechanism for this is found. In any case, analysis of the conditions and requirements for inflow and outflow of cosmic rays in application to the Galaxy as a whole deserves full attention and can serve for judgement about the viability of metagalactic models.

Thirdly, the fact may be used that in both the metagalactic and the interstellar gas cosmic rays produce various secondary products. In this respect, it is rather difficult to detect the production of relativistic electrons and positrons, but observation of γ-rays from the decays of π°-mesons and other particles is on the contrary, relatively easy. Moreover, the γ-astronomical method seems now to be the main hope for further development of high energy astrophysics (see §3*d*).

Assuming that the isotropic intensity I_γ (> 100 MeV) < 3–5 $\times 10^{-5}$ photons cm^{-2} s^{-1} sr^{-1} (see Kraushaar *et al.* 1972) one can see that at $n_{\rm mg} \sim 10^{-5}$ cm^{-3} the energy density $w_{\rm mg}$ should be 1.5–2 orders smaller than the value (17), if cosmic rays are uniformly distributed in all intergalactic space. Thus, the data available testify against the universal metagalactic model (see table 1) if $n_{\rm mg} \gtrsim 10^{-6}$ cm^{-3}. The latter estimate seems very probable, but the value of $n_{\rm mg}$ is not yet established (for one of the ways to determine $N_{\rm mg}$ see, for example, Ginzburg 1973). From the data on the isotropic γ background even at $n_{\rm mg} \sim 10^{-5}$, however, one cannot disprove local metagalactic models (see table 1) in which the estimated $w_{\rm mg} \sim 10^{-12}$ is true only in the environs of the Galaxy. The best and, practically, the only known possibility of determining the density w_{cr} near to the Galaxy is the measurement of a γ-ray flux from the Magellanic Clouds (Ginzburg 1972).

If any metagalactic model is valid, it can be expected that both Magellanic Clouds contain cosmic rays with the energy density (17). For the Magellanic Clouds we have

$$M_{\text{HI, L.M.C.}} \simeq 1.1 \times 10^{42}\,\text{g}, \quad M_{\text{HI, S.M.C.}} \simeq 0.8 \times 10^{42}\,\text{g}, \qquad (18)$$
$$R_{\text{L.M.C.}} \simeq 55\,\text{kpc}, \quad R_{\text{S.M.C.}} \simeq 63\,\text{kpc}.$$

For this, using formula (8), we have

$$F_{\gamma,\,\text{L.M.C.}}\,(>100\,\text{MeV}) \simeq 2 \times 10^{-7}, \quad F_{\gamma,\,\text{S.M.C.}}\,(>100\,\text{MeV}) \simeq 10^{-7}\,\text{photon cm}^{-2}\,\text{s}^{-1}. \qquad (19)$$

Observation of fluxes smaller than (19) will disprove metagalactic models. If the fluxes are approximately the same as, or larger than, these calculated values, one cannot come to sufficiently reliable conclusions since the corresponding density or cosmic rays can, in principle, be produced in the clouds themselves. However, this is not very probable since the clouds are much smaller than the Galaxy and even at the same activity (in cosmic-ray acceleration we may expect that in the clouds the density w_{cr} will be smaller than the galactic one. Unfortunately, even if we do not encounter any additional difficulties, the measurement of the fluxes $F_\gamma\,(>100\,\text{MeV}) \lesssim 10^{-7}$ photons $\text{cm}^{-2}\,\text{s}^{-1}$ will become possible only for the next generation of γ telescopes. In addition spectral measurements must be made, or at least, the flux $F_\gamma\,(>50\,\text{MeV})$ should also be measured.

Summarizing, we should say that we do not see any new arguments in favour of metagalactic models and, as before, think that these models are rather improbable. In such cases, however, the concept of probability has no exact meaning, and attention should surely be fixed not on the evaluations of a 'probability' but on concrete investigations serving to determine the cosmic-ray energy density w_{mg} and the possibility of cosmic rays penetrating the Galaxy from outside.

7. Conclusion

The preparation of this paper gave the present author the occasion to evaluate and, where necessary, to re-evaluate the investigations of the problem of the cosmic-ray origin during the last twenty years. The point of departure was some feeling of dissatisfaction because the fundamental problems, such as the role of metagalactic cosmic rays within the Galaxy, the halo dimensions, the characteristic lifetime of cosmic rays and some others are not yet solved and become in the nature of 'eternal' problems. Thus, the author's favourite galactic model of the origin of cosmic rays with a pronounced halo and with supernovae as basic sources, remains not proved. But physicists and astronomers have, under the pressure of facts, repeatedly denied much deeper and more important ideas or constructions than this model. By virtue of what has been said and under the influence of a stream of different suggestions and doubts expressed constantly in literature the present author was prepared to abandon any old assumptions in favour of some other, better grounded ones. But we were not obliged to do this, in any case on this occasion, and that is one of the conclusions of the present report.

In 1953 the electron component of cosmic rays near the Earth was not yet discovered (this was done only in 1961). There is a lot of information about it at present which on the whole completely corresponds with the radio-astronomical data on relativistic electrons in the Galaxy. It has been proved already (after 1965) that the cosmic-ray electron component is formed in the

Galaxy and not outside it. After the discovery of pulsars (1968) a conviction was strengthened that supernovae (and particularly pulsars that are one of the results of the explosions) can be the main source of cosmic rays observed near the Earth. Gamma-astronomy was born, the first results of which (1968–72) testify to a powerful generation of relativistic particles near the galactic centre and it is very likely that we are dealing here first of all with the proton–nuclear component generation. If this latter conclusion is confirmed reliably, as can be expected in the near future, the galactic model of the cosmic-ray origin will be once again confirmed rather convincingly. All this shows great progress even in answering the 'eternal' questions about the cosmic-ray origin, to say nothing of the impressive achievements in high energy astrophysics as a whole. This is why the above-mentioned feeling of dissatisfaction evaporated to a considerable extent when we came to the present conclusion.

Leaving aside these feelings, and perhaps it would have been better to conceal them altogether, let us enumerate once again the trends of further investigations which seem to be of particular importance for going forward in solving the above mentioned basic questions.

1. Determination of the amount of radioactive isotopes (apparently, first of all ^{10}Be) will permit estimation of some characteristics time $T_{\mathrm{cr,r}}$ for cosmic rays that reach the Earth.
2. Determination of the spectrum of relativistic positrons may serve the same purpose, though the comparison of the age T_{e^+} thus obtained with $T_{\mathrm{cr,r}}$ will require special analysis.
3. An old but yet unsolved problem of obtaining reliable and sufficiently accurate data on the intensity of galactic radio-emission $J_\nu(b, l)$ in a wide frequency band and galactic coordinates range remains. Comparison of these data with the spectrum of the cosmic-ray electron component near the Earth together with the calculations according to the scheme mentioned in §3*b* can, finally, lead to the solution of the problem concerning the form of the galactic radio-halo. The problem of observing a radio-halo in a number of other galaxies at rather long wavelengths ($\nu \leqslant 200$ MHz) also remains unsolved.
4. Determination of the intensity and spectrum of γ-rays from the region of the galactic centre will probably make it possible in the very near future to establish the role of this region as a source of the cosmic-ray proton–nuclear component. Measurement of the γ-ray flux from the Magellanic Clouds is much more difficult but seems possible. Such measurements may prove to be a decisive way of determining the metagalactic cosmic-ray intensity.

This list can, of course, be extended by mentioning a number of other problems in experiment and observation as well as in theory. It has partially been done in §§2–5. More detailed description seems to be out of place here since what has been said is quite enough to realise how interesting and real is the outlook for further investigations in cosmic-ray astrophysics which, particularly with the development of γ-astronomy, is clearly rising to a new level.

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Notes added in proof (November 1974)

1. Concerning the interpretation of the data on the amount of radioactive nuclei see Prished, V. L. & Ptuskin, V. S. *Astrophys. Space Sci.* (in the press).

2. At the Westerbork radiotelescope even at 0.5 m convincing evidence was found of a radio halo for the edge-on galaxy NGC 4631 (private communication by J. H. Oort).

3. New γ-astronomical results show that the excess flux in the direction of the galactic centre is generated in an entensive region between the centre and the Solar System (see for instance Puget, J. L. & Stecker, F. W. 1974 *Astrophys. J.* **191** 323; Dodds, D., Strong, A. W., Wolfendale, A. W. & Wdowczyk, J. 1974 *Nature, Lond.* **250**, 716.