GAMMA ASTRONOMY AND COSMIC RAYS[1)]

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UNLIKE x-ray astronomy, γ astronomy, when it comes to observations, is only in the embryonic state and is not at the center of attention. It is, however, quite probable that the situation will change in the near future; this will perhaps occur after the first γ satellite is launched (just as it happened with the first "Uhuru" x-ray satellite). The point is that a study of cosmic γ rays may not only greatly supplement the data obtained by x-ray astronomy, but may also yield entirely new data which are of principal importance for all of high-energy astrophysics (including the astrophysics of cosmic rays and the problem of their origin). Concretely, only γ astronomy affords a possibility of investigating the proton-nuclear component of cosmic rays away from earth (this component will henceforth be called simply cosmic rays, the electron-positron component will be referred to as relativistic electrons).

1. At the present time only indirect information, obtained predominantly from radio-astronomy data, is available concerning cosmic rays far from the earth. The radio-astronomy data, as is well known, make it possible to find the form of the spectrum of the relativistic electrons (i.e., the dependence of their intensity on the energy), but the spectrum itself and the corresponding electron energy density w_e can be determined only by making additional assumptions concerning the magnetic field intensity H in the emitting region. On the other hand, to find the cosmic-ray energy density w_{cr} we must assume in addition a relation between w_{cr} and w_e. Concretely, it is usually assumed that

$$W_{cr} = \varkappa_r W_e = \varkappa_H^{-1} (H^2/8\pi) V; \qquad (1)$$

Here $W_{cr} = w_{cr}V$, $W_e = w_eV$, and $(H^2/8\pi)V$ are respectively the energies of the cosmic rays, of the relativistic electrons, and of the magnetic field in a source with volume V, while $\kappa_r = (w_{cr}/w_e)$ and $\kappa_H = (H^2/8\pi w_{cr})$ are certain coefficients.

If the radio-emission flux is given by $S_\nu = C\nu^{-\alpha}$ for frequencies in the interval $\nu_1 \le \nu \le \nu_2$, then (for details see [1,2])

$$W_{cr} = \varkappa_r W_e = \varkappa_H^{-1} (H^2/8\pi) V = 0{,}19 \varkappa_H^{-3/7} [\varkappa_r A(\gamma, \nu) S_\nu R^2]^{4/7} (R\varphi)^{9/7},$$
$$H = [48 \varkappa_H \varkappa_r A(\gamma, \nu) S_\nu R^{-1} \varphi^{-1}]^{2/7}, \qquad \gamma = 2\alpha + 1, \qquad (2)$$

where R is the distance to a source with angular dimension $\varphi = L/R$, $V = (\pi/6)L^3$, and $A(\gamma, \nu)$ is a function of γ, ν, ν_1, and ν_2:

$$A(\gamma, \nu) = \begin{cases} \dfrac{2.96\cdot 10^{12}}{(\gamma-2)\,a(\gamma)} \nu^{1/2} \left[\dfrac{y_1(\gamma)\nu}{\nu_1}\right]^{(\gamma-2)/2} \left\{1 - \left[\dfrac{y_2(\gamma)\nu_1}{y_1(\gamma)\nu_2}\right]^{(\gamma-2)/2}\right\} & \text{for } \gamma > 2, \\ 1.44\cdot 10^{13} \nu^{1/2} \ln \dfrac{y_1(\gamma)\nu_2}{y_2(\gamma)\nu_1} & \text{for } \gamma = 2, \\ \dfrac{2.96\cdot 10^{12}}{(2-\gamma)\,a(\gamma)} \nu^{1/2} \left[\dfrac{y_2(\gamma)\nu}{\nu_2}\right]^{(\gamma-2)/2} \left\{1 - \left[\dfrac{y_2(\gamma)\nu_1}{y_1(\gamma)\nu_2}\right]^{(2-\gamma)/2}\right\} & \text{for } 1/3 < \gamma < 2. \end{cases}$$

The values of the coefficients $a(\gamma)$, $y_1(\gamma)$, and $y_2(\gamma)$ are given in the table:

We can then determine from radio astronomy data (knowing also the distance R to the source) the quantities w_{cr}, w_e, and H, and we need to specify only the values of κ_r and κ_H. On earth, $\kappa_r \sim 100$, and under quasi-equilibrium conditions we probably have $\kappa_H \sim 1$. These are the values usually employed, but this implies two far-reaching assumptions. It is perfectly possible that $\kappa_H < 1$ or even $\kappa_H \ll 1$ in nonstationary cosmic-ray sources. Near powerful infrared and optical sources, it is quite feasible to have $\kappa_r \gg 100$, owing to the large energy losses experienced by the electrons. In some cases, when it is the electrons that are mainly accelerated, it is possible to have $\kappa_r \ll 100$.

The determination of the field H (or of the quantity $\kappa_r\kappa_H$) in addition to w_e is possible in principle by using simultaneously radio and x-ray data, if the radio emission in synchrotron radiation and the x-rays are due to Compton back scattering of the same relativistic electrons by the known radiation field. However, even in this case (insofar as we know, such a possibility was not considered in fact for any source whatever), it is still impossible to determine the cosmic-ray energy W_{cr} without specifying also the value of κ_r or κ_H. It is these circumstances that cause the essential uncertainty concerning the cosmic-ray intensity in the universe. In particular, the energy density of the cosmic rays $w_{cr,Mg} \equiv w_{Mg}$ in the metagalaxy or in its parts adjacent to our galaxy has not yet been determined Metagalactic models of the origin of cosmic rays therefore continue to be discussed[3-5], and are sometimes even preferred. In such models $w_{Mg} \approx w_G$, where $w_G \equiv w_{cr,G} \sim 10^{-12}$ erg/cm^3 is the energy density of the cosmic rays on earth, and, by assumption, in a considerable part of the galaxy.

The author has expressed his own opinion many times concerning this question[2,6-9]. According to

γ	1	1.5	2	2.5	3	4	5
$a(\gamma)$	0.283	0.147	0.103	0.0852	0.0742	0.0725	0.0922
$y_1(\gamma)$	0.80	1.3	1.8	2.2	2.7	3.4	4.0
$y_2(\gamma)$	0.00045	0.011	0.032	0.10	0.18	0.38	0.65

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this opinion, the metagalactic models of the origin of cosmic rays are much less reliable than the galactic ones. The main arguments are based on energy and are connected with gamma-astronomy data. We shall not repeat them here[2)]. It is important that all these and other arguments still do not constitute a proof, especially with respect to the local metagalactic models, in which $w_{Mg} \approx w_G$ only in a certain limited region near our galaxy.

Since the number of relativistic electrons in the metagalaxy is certainly less than on earth (see[8]), $\kappa_r \gg 100$ far from the galaxy in metagalactic models. It is difficult to doubt that in these models $\kappa_H \ll 1$ in the intergalactic space, for when $\kappa_H \sim 1$, (i.e., when $w_{Mg} \sim H^2_{Mg}/8\pi \sim w_G \sim 10^{-12}$), the field is $H_{Mg} \sim 5 \times 10^{-6}$ Oe.

Thus, we cannot use the radio and x-ray data for a decisive conclusion concerning the fate of metagalactic models and, most importantly, for a determination of the intensity of the cosmic rays in remote regions of the galaxy, in radio galaxies, etc., and a new independent method is necessary. As already mentioned (and has been known on the whole for a long time), such a method is indeed the study of cosmic γ rays[2,6,10-15].

2. The protons and nuclei contained in the cosmic rays experience collisions with the protons and nuclei of the intergalactic or interstellar gas. The nuclear collisions produce, in particular, π^0 mesons and Σ^0 hyperons, which decay rapidly to form γ rays. π^0-meson decay proceeds with probability 98.8% (i.e., practically always) via the channel $\pi^0 \to 2\gamma$, by virtue of which the energy of the γ rays from the decay of the π^0 meson at rest is equal to $E_\gamma = m_\pi c^2/2 = 67.5$ MeV; the average lifetime of the π^0 meson is 0.84×10^{-16} sec. The Σ^0 hyperon decays (with practical probability 100%) via the channel $\Sigma^0 \to \Lambda + \gamma$, the energy is $E_\gamma \approx 77$ MeV, and the average Σ^0-hyperon lifetime is less than 10^{-14} sec. In addition to being directly produced in nuclear collisions, the π^0 mesons are also produced as a result of the decay of different mesons and hyperons ($K^\pm \to \pi^\pm + \pi^0$, $\Lambda \to n + \pi^0$ etc.), by virtue of which γ rays are again produced. The probabilities and kinematics of all the significant reactions are quite well known[13,14] and make it possible to calculate the γ0 γ-ray spectrum with an accuracy that is perfectly adequate from the point of view of the discussed astrophysical applications. It is important here that the flux of cosmic γ rays is generated, of course, not by monoenergetic particles, but cosmic rays that are isotropic directionwise and have a certain intensity $I_{cr}(E)$. Averaging over the spectrum therefore takes place, and concretely, the intensity of the γ rays with energy E_γ is equal to

$$I_\gamma(E_\gamma) = N(L)\int_{E_\gamma}^{\infty} \sigma(E_\gamma, E)\, I_{cr}(E)\, dE, \tag{3}$$

where σ is the corresponding effective cross section averaged with allowance for the chemical composition of the cosmic rays and of the gas (account is also taken, of course, of the fact that two photons are produced in the decay of π^0 meson), and $N(L) = \int_0^L n(\mathbf{r})dr$ is the number of particles in the gas along the line of sight (in (3) and below, the intensity I_{cr} is assumed to be independent of the coordinates). The integral intensity is

$$I_\gamma(>E_\gamma) = \int_{E_\gamma}^{\infty} I_\gamma(E_\gamma)\, dE_\gamma.$$

The flux of γ rays from a discrete source is

$$F_\gamma(>E_\gamma) = \int_\Omega I_\gamma(>E_\gamma)\, d\Omega \approx \frac{(\overline{\sigma I_{cr}})\, N(V)}{R^2} = \frac{5\cdot 10^{23}\,(\overline{\sigma I_{cr}})}{R^2} M \text{ photons/cm}^2\text{sec}, \tag{4}$$

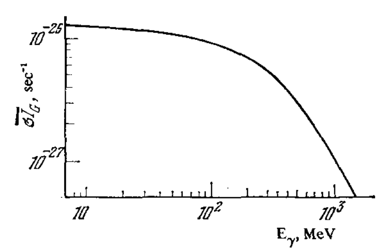
where Ω is the solid angle, R is the distance to the source (in cm), $N(V) = nV$ is the number of particles (nuclei) in the source (volume V, average gas concentration n), and $M = 2 \times 10^{-24} N(V)$ is the mass of the gas in the source in grams (the chemical composition of the source is assumed to correspond to the average abundance of the elements and therefore, especially to take into account the He nuclei, the mass of the "average" nucleus in the gas is assumed to be 2×10^{-24} g). For the cosmic-ray spectrum at the earth (intensity $I_G(E)$), the value of

$$(\overline{\sigma I_{cr}}) = (\overline{\sigma I_G}) = \int_{E_\gamma}^{\infty}\int_{E=E_\gamma}^{\infty} \sigma(E_\gamma, E) \times I_G(E)\, dE\, dE_\gamma$$

is shown in the figure, which is taken from[13]. We shall use henceforth the value $(\sigma I_G)E_\gamma = 100$ MeV $= 10^{-26}$ sec^{-1}, and consequently

$$F_\gamma(E_\gamma > 100\,\text{MeV}) = \frac{10^{-26} nV\,(w_{cr}/w_G)}{R^2} = \frac{5\cdot 10^{-3} M\,(w_{cr}/w_G)}{R^2} \text{ photons/cm}^2\text{sec}, \tag{5}$$

where w_{cr} is the energy density of the cosmic rays in the source, under the assumption that their spectrum has the same form as on earth (therefore $w_{cr}/w_G = I_{cr}/I_G$). Within the limits of this approximation we have for sources of such as our galaxy, where non-ionized atomic hydrogen predominates, $M \approx 1.2 M_{HI}$, where M_{HI} is the mass of neutral hydrogen; the accuracy of the calculations can be increased in this case, since the data on the hydrogen line ($\lambda = 21$ cm) yield the ratio M_{HI}/R^2 directly. We shall attempt



[2)]We note only that according to the refined data of [10] the intensity of the metagalactic γ rays, $I_\gamma(E_\gamma > 100$ Mev$) < 3 \times 10^{-5}$ photon/cm^2 sec-sr, i.e., smaller by at least a factor of 3 than the value used in [8]. This circumstance strengthens the arguments advanced in [8] against certain metagalactic models. In connection with [4], we note also that, as emphasized in [7] (see also [2]), stationary cosmology and local theory of quasars "have not been confirmed and meet with objections. Therefore the metagalactic theory of the origin of cosmic rays, in which we are now interested, does not receive additional support from the mentioned hypothesis." These and other remarks pertaining to articles [2,7], as can be readily seen, have nothing in common with respect to their character and tone with the author's arguments contained in [4] (Sec. 5).

such refinements, which are still not important at present.

We note, finally, that the spectrum of γ rays of "nuclear" origin, with which we are dealing, is concentrated for understandable reasons mainly in the energy region $E_\gamma \gtrsim 50-100$ MeV (the red shift is disregarded here, of course, and we therefore have in mind sources that are not too remote). The foregoing can be seen from the figure and more concretely from the following example[15]: for γ rays from π^0-meson decay we have the ratio

$$\xi = \frac{F_\gamma(E_\gamma > 50\,\text{MeV}) - F_\gamma(E_\gamma > 100\,\text{MeV})}{F_\gamma(E_\gamma > 100\,\text{MeV})} = 0.12.$$

At the same time, $\xi = 2.03$ for relativistic electrons with spectrum $I_e(E) = KE^{-2.6}$ in case of bremsstrahlung γ rays and $\xi = 0.74$ for γ rays from synchrotron radiation or Compton back scattering. Thus, spectral measurements of the γ-ray flux make it possible to establish their nuclear nature in principle. If this is done, then from the changes of the flux $F_\gamma(E_\gamma > 100$ MeV) or the corresponding intensity I_γ we immediately obtain the ratio w_{cr}/w_G in the source, i.e., the main parameters which we are missing at present. It is assumed here, of course, that the cosmic-ray spectra in the source and on earth are similar. But for such an assumption, first, there are certain grounds, and second, under real condition it may apparently turn out to affect only a numerical coefficient of the order of unity. At any rate, the determination of the energy density w_{cr} or of the total energy $W_{cr} = w_{cr}V$ of cosmic rays in sources, even by the method indicated above, would be a fundamental forward step and, I am convinced, a most important accomplishment of high-energy astrophysics.

3. So far we did not touch upon concrete astronomical objects. Yet this must be done, for otherwise the possibility of γ astronomy turn out to be insufficiently clear. We shall therefore discuss two examples, the Magellanic clouds and the central region of the galaxy.

An examination of the Magellanic clouds is of interest, of course, in itself. However, from the point of view of the present article this example is particularly important and is connected with attempts to answer the following question: how is one to determine most convincingly the fate of metagalactic models of the origin of cosmic rays? To this end it suffices to determine the energy density of the cosmic rays w_{Mg} in the region surrounding the galaxy. If it turns out that $w_{Mg} \ll w_G \sim 10^{-12}$ erg/cm^3, then the metagalactic models are eliminated. The best way we know to solve this problem is just the measurement of the γ-ray flux from the Magellanic clouds[16]. For these clouds (the large cloud LMC and the small cloud SMC) the distances to the sun and the mass of the neutral hydrogen are respectively[17]

$$R\,(\text{LMC}) = 55\,\text{kps},\quad R\,(\text{SMC}) = 63\,\text{kps},$$
$$M_{HI}\,(\text{LMC}) = 1.1\cdot 10^{42}\,\text{g},\quad M_{HI}\,(\text{SMC}) = 0.8\cdot 10^{42}\,\text{g}.$$

Therefore, according to (5), at $w_{cr} = w_G$ we have

$$F_{\gamma,\,\text{LMC}}\,(E_\gamma > 100\,\text{MeV}) \approx 2\cdot 10^{-7},\ F_{\gamma,\,\text{SMC}}\,(E_\gamma > 100\,\text{MeV}) \approx \approx 1\cdot 10^{-7}\ \text{photons/cm}^2\text{sec}. \qquad (6)$$

As already mentioned, these fluxes can also be calculated more accurately. Another fact is important here, namely, the fluxes (6) are obtained directly in all known metagalactic models, for the intrinsic cosmic-ray sources play a minor role in these models in the Magellanic clouds, as well as in the galaxy, and therefore $w_{Mg} \approx w_G \approx w_{SMC} \approx w_{LMC}$. In the galactic models, to the contrary, there are no grounds for expecting such an equation to hold. Even if the activities of the cosmic-ray sources are equal it is quite likely that $w_G > w_{LMC} > w_{SMC}$, by virtue of the small dimensions of the clouds and accordingly the faster escape of cosmic rays from them. In addition, the galaxy contains apparently a powerful central source of cosmic rays (see below), whereas there is probably no such source in the clouds.

Thus, for a convincing refutation of the metagalactic models of the origin of cosmic rays[3)] it would be sufficient to establish, for example, that from both clouds taken together we have $F_{\gamma,MC}(E_\gamma > 100\text{ MeV}) \ll 3 \times 10^{-7}$ or that $F_{\gamma,SMC} \ll F_{\gamma,LMC}/2$. When the calculations are made more precise, the indicated inequalities ($\ll$) can in principle be replaced by weaker ones ($<$). It is important here that any contribution to the γ ray flux from the relativistic electrons leads only to an increase of the fluxes F_γ, and by the same token cannot influence in any way the indicated interpretation, say, of the result $F_{\gamma,MC}(E > 100\text{ MeV}) \ll 3 \times 10^{-7}$. We shall call such a result "negative" and note that there exists, as is frequently the case, a certain asymmetry in affirmative and negative results of an experiment. Thus, if the measurements of the γ-ray flux from the Magellanic clouds were to reveal the presence of a noticeable flux $F_{\gamma,MC} \gtrsim 3 \times 10^{-7}$ (we define such a result arbitrarily as affirmative), this still does not prove the validity of the metagalactic models, for such a flux can in principle be generated also by cosmic rays (and also by relativistic electrons) accelerated in the clouds themselves. In one way or another, there is no doubt that it is extremely desirable to measure the γ-ray flux from the Magellanic clouds. This is not easily done, for at the present time we can measure only fluxes F_γ ($E_\gamma > 100$ MeV) $\sim 10^{-5}$ photon/cm^{2}sec[18,19]. There are, however, realistic prospects, particularly with prolonged observations from satellites, of measuring also much smaller fluxes[18-20], apparently down to 10^{-7}. In the case of a known object, the possibility of prolonged tracking greatly facilitates the problem, and thus the discussed possibility of investigating the γ radiation from the Magellanic clouds seems perfectly realistic.

4. Because this problem is nevertheless complicated, and to no less a degree from independent considerations, it is of particular interest to determine the γ radiation from the central region of the galaxy. Such radiation (with $E_\gamma > 100$ MeV) was already observed, and the intensity of the corresponding ("equivalent") linear source is[10] $(1.2 \pm 0.3) \times 10^{-4}$ or, according to[15], $(2.0 \pm 0.6) \times 10^{-4}$ photon/cm^{2}sec-rad. If we multiply this value by an angular resolution of

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3)It is important that we are referring here to all the known models, whereas measurements of the isotropic background of the γ rays can serve as a refutation of only those models in which the cosmic rays fill a very large region, particularly all of metagalactic space (furthermore, the density of the metagalactic gas has not yet been established.

approximately $\pi/6$ (see[10]), we obtain for the flux from the central galactic source (we take into account here also the flux value $(4.9 \pm 1.8) \times 10^{-5}$ photon/cm²sec, given in[21] on the basis of the data of[10])

$$F_\gamma (E_\gamma > 100\text{MeV}) = (3-10)\cdot 10^{-5} \text{ photons/cm}^2\text{sec}. \quad (7)$$

To be sure, doubts were expressed[19] with respect to the extent to which this result is realistic and can be interpreted as evidence of the existence of an extended source of γ rays at the center of the galaxy, but these doubts are most likely not justified, although of course the question can be resolved only by new observations. In particular, it is necessary to ascertain also the existence in the galactic plane and near this plane of discrete (local) γ-ray sources, indication with respect to which can be found in the literature[19]. It is important to emphasize here that we are dealing with fluxes on the order of 10^{-5}—10^{-4}, which certainly can be measured by already known methods; it is therefore difficult to doubt the possibility of obtaining definite results. We shall assume here that the value (7) is realistic. Then, on the basis of spectral measurements[15] 4), and also from the number of indirect considerations, it is most probable that we are dealing with γ rays generated by cosmic rays (i.e., mainly with the products of π^0-meson decay). Assuming such an interpretation, we shall draw several conclusions[22].

Substituting the value of (7) in (5), we arrive at the conclusion that in the central galactic source (subscript c) there are concentrated cosmic rays with total energy

$$W_c = w_c V_c \approx (3-10)\cdot 10^{66} (w_G/n_c) \sim (3-10)\, 10^{54}/n_c \text{ erg}. \quad (8)$$

since $w_G \sim 10^{-12}$ erg/cm³ and the distance from the sun to the central source is R = kps. If the central source is not assumed to be small (i.e., if its characteristic dimension L_c is not assumed to be smaller than or of the order of 300 ps), then the gas concentration n_c cannot be assumed larger than approximately unity (at $L_c \sim 10^{21}$ cm the volume is $V_c \sim 10^{63}$ and the mass of the gas is $M_c \sim 2 \times 10^{-24} n_c V_c \sim 2 \times 10^{39} n_c \approx 10^6 n_c M_\odot$; at n_c we already have $M_c \sim 10^7 M_\odot$, which probably is the limit for the region with the chosen volume). At $n_c \sim 1$ we get from (8) the estimate $W_c \sim (3-10) \times 10^{54}$ erg, which is smaller by only one order of magnitude than the total energy of the cosmic rays in the galaxy[2,7,23]. On the other hand, it is precisely a value on the order of 10^{55} erg that is obtained from an analysis of astronomical data, that indicates a galactic-nucleus explosion occurring approximately 10^7 years ago[24,25] (similar values for the kinetic energy and for the energy of the cosmic rays released in explosions of the galactic nucleus were used back in[6], pp. 209–210).

If the dimension of the central γ source were smaller than 200—300 ps, then a value $n_c \gtrsim 10$ could not be excluded. The energy W_c, of course, would decrease in this case (see (8)) but the intensity of the cosmic rays $I_{cr,c} \equiv I_c$, generally speaking, would not decrease. For example, at $n_c \sim 10$ and $V_c \sim 10^{63}$ we obtain from (8) $W_c \sim (3-10) \times 10^{53}$ and $I_c/I_G = w_c/w_G \sim 3 \times 10^2$—$10^3$. It seems quite difficult to confine cosmic rays in a smaller region for 10^7 years (for example, at $T_c \sim 3 \times 10^4$ sec the diffusion path is $L \sim (2DT_c)^{1/2} \sim 10^{21}$ at $D \sim 10^{27}$ cm²sec⁻¹, corresponding to a very small value $l \sim 0.03$ ps for an effective mean free path $l \sim D/v$, $v \sim 10^{10}$ cm/sec). Therefore the value $W_c \sim 3 \times 10^{53}$ seems to us to be the minimum possible one, and more likely $W_c \gtrsim 3 \times 10^{54}$ erg. In this case the central source of cosmic rays will be important from the point of view of the entire energy balance of the cosmic rays in the galaxy (the average injection power is $U_c \sim W_c/T_c \gtrsim 10^{40}$ erg/sec, which coincides in order of magnitude with the total injection power in galactic models[2,6,23]).

If the value in (7) is correct, then the central source emits $\Phi_\gamma(E_\gamma > 100 \text{ MeV}) = 4\pi R^2 F_\gamma \sim (3-10)\cdot 10^{41}$ photons/sec, corresponding to a luminosity $L_\gamma \sim \Phi_\gamma \bar{E}_\gamma \sim 10^{38}$ erg/sec. At the same time, the entire galaxy, where it to be uniformly filled with cosmic rays, would emit $\Phi_{\gamma,G}(E_\gamma > 100 \text{ MeV}) = 5\cdot 10^{-3}\cdot 4\pi M_g \sim 3\cdot 10^{41}$ photons/sec, since the total mass of the gas of the galaxy is $M_g \approx 5 \times 10^{42}$ g (see [44]).

If subsequent measurements ultimately prove the existence of a central γ-ray source of "nuclear" (more accurately, π^0-mesic) nature, and this can be expected in the near future, then we shall obtain by the same token one more weighty argument against the metagalactic models of the origin of cosmic rays, for in these models the principal and predominant sources of cosmic rays in the galaxy are other galaxies and quasars. Moreover, if the energy of the cosmic rays that have been produced in explosions of the galactic nucleus and still remain in the central region reaches 10^{55} erg, then it becomes superfluous to assume metagalactic sources even if we do not take into account the generation of cosmic rays in supernovas (including the contribution from pulsars; actually however, one can assume the role of the supernovas to be appreciable).

The situation is not confined to the foregoing, since it is possible (and necessary) to compare the γ-astronomy data with the radio-astronomical results. Unfortunately, in case of an extended source of nonthermal radio emission in the central region of the galaxy we possess only the old data of[26] (see also[27]). According to these data, the flux from an extended source with dimensions 1° × 3° (probable volume $V \sim 10^{63}$ cm³) amounts to $S_\nu = 3 \times 10^{-20}$ erg/cm²sec-Hz at a frequency $\nu = 85.5$ MHz, and the spectral index is $\alpha = 0.7$ ($\gamma = 2\alpha + 1 = 2.4$). Substituting these parameters in (2) we arrive in the case of a central radio source to the values (the subscript r following c indicates the use of radio data)

$$W_{c,r} = \varkappa_r W_{e,r} \sim 3\cdot 10^{51} \varkappa_H^{-3/7} \varkappa_r^{4/7} \text{ erg}, \quad H \sim 10^{-5} (\varkappa_H \varkappa_r)^{2/7} \text{Oe}, \quad (9)$$

where the radio emission is assumed to have a spectral index $\alpha = 0.7$ in the interval 10^7—10^9 Hz; the estimates are not particularly sensitive to the choice of this interval, and within certain limits also to the choice of the other parameters. If we now assume, as on earth, $\kappa_r \sim 100$ and $\kappa_H \sim 1$, then (at $V_c \sim 10^{63}$) we have

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4) In [15] they measured precisely the ratio $\xi = [F_\gamma(E_\gamma > 50 \text{ Mev}) - F_\gamma(E_\gamma > 100 \text{ Mev})]/F_\gamma(E_\gamma > 100 \text{ Mev})$, which turned out to be less than 0.5. It was therefore concluded in [15] that the probability that the γ rays are of Compton or synchrotron origin is only 6%.

$$W_{c,r} \sim 3\cdot10^{52}\,\mathrm{erg},\ W_{e,r} \sim 3\cdot10^{50}\,\mathrm{erg},\ H \sim 3\cdot10^{-5} \sim 10H_G,$$
$$w_{c,r} = W_{c,r}/V_c \sim 3\cdot10^{-11} \sim 30w_G,\quad w_{e,r} = W_{e,r}/V_c \sim 3\cdot10^{-13} \sim 30w_{e,G}. \tag{10}$$

For all the roughness of the initial data (and therefore also to a certain degree of the estimates), the presented value of $W_{c,r}$ is much smaller than the value $W_c \sim 3\times10^{53}-10^{55}$ erg determined above from the γ data. It is undoubtedly necessary to refine the data, but if the discrepancy is real (and the author is inclined to think so), then it is at the same time perfectly natural and can be due to the presence of a powerful infrared source in the central region[28]. In fact, in a strong radiation field the electrons experience large Compton losses, by virtue of which the value $\kappa_r = w_{cr}/w_e$ can greatly exceed the earth value used above. At $\kappa_r \sim 10^4$ we already have $W_{c,r} \sim 5\times10^{53}$ erg. In addition, it is perfectly possible that in the central region $\kappa_H < 1$ or even $\kappa_H \ll 1$, since there are no particular grounds for the energy of the cosmic rays to be equal to the energy of the magnetic field in the nonstationary region.

The conclusion that $\kappa_r \gtrsim 10^2$ in the central region is in direct contradiction with the conclusion in[5], where the value $\kappa_r \sim 5$ is regarded as probable. Such a conclusion can be arrived at, however, only by making three assumptions: first, by ignoring completely the γ-astronomy data and their probable connection with π^0-meson decay; second, by putting $\kappa_H \sim 1$; third, by assuming that the x-rays from the central source GCX (see[29]) are the product of Compton back scattering. At present we see no grounds whatever for any of these assumptions. In particular, according to[30], x-ray data yield $\alpha = 1.37 \pm 0.05$, and not $\alpha = 0.7$ as is assumed for the radio band. It is perfectly possible that it is not the Compton mechanism that acts in the GCX x-ray source, and this source may in general turn out to be an aggregate of discrete sources (see, for example,[31]). At the same time, even if further measurements have changed the situation and have led to agreement between the values of the index α and the angular dimensions of the extended source in the radio and in the x-ray bands, it is still impossible to draw any convincing conclusions concerning the intensity of the cosmic rays (meaning also concerning the value of κ_r) in the central region. As already noted, this is due to our not knowing the coefficient κ_H.

5. Summarizing, we can state that only measurements of the flux of the γ rays and of their spectrum in the energy region $E_\gamma \gtrsim 50$ MeV will make it possible to determine the intensity and the energy of the proton-nuclear component of the cosmic rays far from the earth (in addition to the flux $F_\gamma(E > 100\ \mathrm{MeV})$, it suffices to know at least the already mentioned ratio ξ that characterizes this spectrum). This procedure is certainly feasible if a powerful central source exists in the galaxy. According to the available data, such a source does exist, and the total cosmic-ray energy in it is $W_c \sim 3\times10^{53}-10^{55}$ erg, while the average energy density is $w_c = W_c/V_c \gg w_G \sim 10^{-12}$ erg/cm^3. It is possible that $\kappa_r \gg 100$ and $\kappa_H < 1$ in this series. Another particularly attractive object for the solution of important problems (meaning primarily the fate of the metagalactic models of the origin of cosmic rays) are the Magellanic clouds. In this case, however, to measure the γ-ray flux one needs apparatus of high sensitivity, the possibility of developing of which in the nearest future is probable, but not yet proven.

We have focused our attention above on γ rays of "nuclear" origin, i.e., those produced in nuclear collisions of cosmic rays in a gas. Moreover, in this case we have dealt with energy $E_\gamma \gtrsim 50-100$ MeV.[5)] Yet there are many other known possibilities in γ astronomy[11-13,18,19,22,45]. Thus, interest attaches to the energy region $E_\gamma = 1-50$ MeV, which receives π^0-meson decay γ rays from objects having a large red-shift parameter z (concretely, we have in mind here γ radiation in the Lemaitre model[33], annihilation of matter and antimatter [34] at $z \gg 1$, etc.). Of course, at $E_\gamma < 50$ MeV the competition of processes that differ from π^0 decay is much more appreciable than at $E_\gamma > 50$ MeV. Nonetheless, there do exist certain possibilities of performing measurements also in the energy region $E_\gamma \sim 1-50$ MeV (see[18,19,34]). The same can be said of observations of γ rays with energy $E_\gamma > 10^{11}$ eV, which are carried out by observing Cerenkov radiation in the atmosphere[18,19,35]. Worthy of particular mention are γ rays emitted by excited nuclei produced in nuclear reactions (see in particular[32]), and γ radiation from the annihilation of positrons and electrons (if we disregard the red shift, then these γ rays should be concentrated about $E_\gamma = 0.511$ MeV). Finally, there is no doubt of the importance of the study of the γ rays generated, like the x-rays, by electrons of sufficiently high energy (we have in mind bremsstrahlung and synchrotron radiation, and also the Compton back scattering of relativistic electrons by infrared, optical, and x-ray photons)[6)].

It is possible that one of the just mentioned trends and objects of research in γ astronomy will lead to very significant results. Nonetheless, it seems to us that at the present time the principal task in γ astronomy, one decisive for its subsequent development as a whole, is the study of the photons generated by the

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5)In the energy region $E_\gamma \gtrsim 50-100$ MeV, great interest attaches, in addition to the indicated measurements, also to a study of the isotropic background. An important role will be played here by any lowering of the presently established upper intensity limit $I_\gamma(E > 100\ \mathrm{Mev}) < 3\times10^{-5}$ photon/cm^2 sec-sr (see [10]). Knowledge of the upper limit of I_γ, and all the more of the corresponding value of I_γ, would make it possible to draw definite conclusions concerning the metagalactic cosmic rays (see [8,13] and the bibliography therein), and also determine to a considerable degree the minimum observable flux F_γ from discrete sources.

6)X-rays (energy less than several hundred keV; the name x-ray photons is sometimes used only for photons with energy less than 100 keV) are emitted mainly by electrons, and furthermore as a result of the already mentioned bremsstrahlung and synchrotron radiation processes and also Compton back scattering. In the region of soft x-rays, interest attaches also to characteristic x-ray lines, especially of iron. Theoretical questions connected with x-ray astronomy are discussed in [11,36-39]. The status of x-ray astronomy and also of astronomy by the middle of 1969 is discussed in the collection [36] (in Usp. Fiz. Nauk, question of x-ray astronomy were discussed or touched upon in the articles [11,18,40-43]). X-ray data obtained during the last three years are contained in many articles, printed primarily in the astrophysical journals (mainly in Astrophysics Journal Letters) and in "Nature", among these articles are the cited [29-31].

proton-nuclear component of the cosmic rays. The extraction of appropriate reliable data for the galaxy (primarily for its central region) and for the Magellanic clouds, let alone more remote sources, is a most important accomplishment of high-energy astrophysics (in particular, this will be very valuable for progress in the problem of the origin of cosmic rays). At the present time it is hardly necessary to demonstrate that high-energy astrophysics has in turn already become an indispensible and important part of all of astrophysics.

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