Origin of cosmic rays

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Abstract. The object of the report is to review the state of the problem of the origin of cosmic rays taking into account the papers which have appeared since the Jaipur Conference (India, 1963). Besides a series of concrete remarks and discussion of new data, the report gives a fairly detailed discussion of the role of plasma effects connected with cosmic rays in different regions of the universe (galaxies, radiogalaxies, metagalactic space). The plasma phenomena are in the author's opinion of fundamental importance to the astrophysics of cosmic rays.

The aim of this report is to elucidate the problem of the origin of cosmic rays (or, using a more recent and accurate term, the state of cosmic ray astrophysics) taking into account those new investigations which have appeared after the Jaipur 1963 Conference in India. Just as in our report submitted to the Indian Conference (Ginzburg and Syrovatsky 1963 a) we shall not attempt here to cover the material as extensively and elaborately as is possible (see Ginzburg and Syrovatsky 1963 b) but shall merely deal with selected problems.

1. On solved and unsolved problems of cosmic ray astrophysics

The explosive-rate development and unquestionable progress made in cosmic ray astrophysics in the past 10 to 15 years must not, of course, overshadow the fact that there are quite a few essential obscurities in the field.

We shall therefore begin by discussing briefly the current situation in terms of answering this question: what is clear and what is unclear in cosmic ray astrophysics?

Today there is hardly any doubt that along with stars and interstellar gas cosmic rays belong to the basic elements out of which the galaxies and the universe as a whole are composed. This conclusion stems not only from, and even not so much from, the fact that cosmic rays are observed in widely different objects (galaxies, radiogalaxies, quasars, the envelopes of supernovae, the Sun) as from a relatively large density of the energy and pressure of cosmic rays. Thus, even in the Galaxy which is 'normal' in the radio band the cosmic ray energy density $w_G \sim 10^{-12}$ erg cm^{-3}. At the same time the strength of the galactic magnetic field $H_G \sim 3$ to 10×10^{-6} Oe is such that $H_G^2/8\pi \sim w_G$; the inner energy density $w_T \sim nkT$ of a gas with concentration $n \sim 1$ and temperature $T \sim 10^4$ °K is the same in the order of magnitude and hence in most areas of the Galaxy we have $w_T \lesssim w_G$. In radio galaxies there occur cosmic ray energy densities w_g which are sometimes higher than w_G by several orders. There can be hardly any doubt as to the fact that the energy and pressure of cosmic rays play an essential and in some cases probably decisive role for understanding the dynamics of galactic haloes, envelopes of supernovae, radio-emitting clouds in radiogalaxies (e.g. Cygnus A), and also outbursts, emitting in a continuous spectrum, in radiogalaxies and quasars (Virgo A = NGC 4486, 3C273B etc.) etc.

Another factor that must be stressed is the general occurrence of the effective acceleration of cosmic rays. This means that the acceleration of cosmic rays (i.e. the generation of relativistic particles) is not an exceptional effect observed under special conditions but something observed as a rule: particles accelerate effectively in the Sun, in the Earth's radiation belt, in the outbursts of stars, and in radiogalaxies. The result is in general quite understandable in terms of the current concepts of plasma physics and magnetohydrodynamics. Indeed, the plasma state in which there are different motions (beams, jets, waves, etc.) but no magnetic field and fast particles is, in general, unstable. Therefore, even if an outburst (e.g. a supernova outburst) could be considered at its earliest stage without taking into account the effect of the field and cosmic rays, the latter would appear anyway after some time. The question as to the level to which the energy of a field and that of the cosmic rays may rise can have no universal answer: the answer depends on the time of the process and other factors. However, in some cases we can expect a certain quasi-equilibrium at which the densities of energies of different types are equal in order of magnitude, i.e.

$$w_{cr} \sim H^2/8\pi \sim \rho u^2/2 \qquad (1)$$

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

Apart from the above general conclusions there are radioastronomical data on the spectrum of the electron component of cosmic rays in different areas and objects (Ginzburg and Syrovatsky 1963 b, Kellermann 1964) as well as information about the cosmic rays near the Earth (Ginzburg and Syrovatsky 1963 b, Webber 1964). We shall confine ourselves here to some brief conclusions.

The chemical composition of the cosmic rays near the Earth indicates that the constituent relativistic nuclei have passed from 2 to 10 g cm^{-2}; for the average interstellar gas density (in the area occupied by the cosmic rays) $\rho \sim 10^{-26}$ g cm^{-3}, this corresponds to the path $L \sim 5 \times 10^{26}$ cm and the time $T \sim L/c \sim 10^{16}$ sec $\sim 3 \times 10^8$ years. The sources of galactic cosmic rays must either be anomalously rich in nuclei of the M and H groups, or, which is more probable, the acceleration of such nuclei must be more effective than that of protons and α particles.

The data on the electron-positron component (Ginzburg and Syrovatsky 1963 b, Webber 1964) agree roughly with the radioastronomical data on the one hand and confirm, on the other, the conclusion that the main part of the electrons in the cosmic rays near the Earth are primary (i.e. these electrons are not products of $\pi \rightarrow \mu \rightarrow e$ decay) (Ginzburg and Syrovatsky 1963 a, b, 1964 a).

The entire body of all available data is, in our opinion, quite compatible with the galactic theory of the origin of cosmic rays near the Earth, except for particles with energies $E \gtrsim 10^{16}$ to 10^{17} eV which most likely enter the Galaxy from outside and are generated, for example, in radiogalaxies (below, however, we mean only the main part of cosmic rays which corresponds to the energies $E \lesssim 10^{13}$ to 10^{15} eV). The main sources of cosmic rays in the Galaxy are supernovae and, perhaps, the outbursts of the galactic nucleus. These sources must ensure the injection of cosmic rays into interstellar space with a subsequent power*

$$U_{cr} \sim 10^{40} \text{ to } 10^{41} \text{ erg sec}^{-1}$$
$$U_e \sim 3 \times 10^{38} \text{ to } 3 \times 10^{39} \text{ erg sec}^{-1}. \quad (2)$$

Here U_{cr} applies to all cosmic rays and U_e to their electron component.

The powers (2) are very large (e.g. the value $U_{cr} \sim 3 \times 10^{40}$ is obtained if the flares of supernovae occur in the Galaxy on the average once in a hundred years, 10^{50} ergs passing into the cosmic rays per flare on the average) but still permissible with respect to the above sources (see section 4). At the same time there are no independent data which would confirm that this injection is really effected by the galactic sources. This is why the crucial problem in the theory of cosmic rays in the Galaxy, viz. the problem of a possible role of the flow of cosmic rays of a metagalactic origin into the Galaxy, remains incompletely solved. Section 2 of this report is concerned with the above problem and metagalactic cosmic rays in general. Here we shall enumerate other unclear or insufficiently clear problems.

(i) In near-Earth observation the cosmic rays† have in the low energy region a maximum in the energy spectrum, this maximum being also observed even at solar minimum (Webber 1964, I. Dorman and L. Dorman 1965). Hence this important question arises: does the spectrum maximum exist in interstellar space as well or is it produced completely by the effect of the interplanetary medium (the action of irregularities in the solar wind, etc.)? It is the last conclusion that is reached (I. Dorman and L. Dorman 1965). But then we must understand why the cosmic rays far from the solar system have no maximum in the spectrum in the energy region under discussion, $E \gtrsim 10^8$ eV/nucleon, despite the increase of ionization losses in the transition to non-relativistic energies. Of course, the question as to the position of the maximum in the spectrum is quantitative, and even the absence of this maximum at $E > 10^8$ eV/nucleon is not contradictory until a final analysis has been made. Now, it is just the need to solve the problem of the spectrum in the low energy region that we want to emphasize here.

(ii) The anisotropy of cosmic rays does not seem to have been discovered in any energy region. Even if anisotropy is observed in solar minimum years (Ginzburg and Syrovatsky 1963 b, Webber 1964), it does not at any rate exceed a fraction of one per cent for the main part of cosmic rays. A practically complete isotropy of cosmic rays is in agreement with the galactic theory using the diffusion approximation (Ginzburg and Syrovatsky 1963 b). On the other hand, the character of diffusion (propagation) of cosmic rays in the Galaxy and in magnetic fields in general is insufficiently clear. Therefore, it is quite possible that the isotropy of cosmic rays reflects directly the specific movement of cosmic rays in interstellar plasma. We shall see below that there are good reasons for this point of view.

(iii) Speaking of unclear problems, mention should be made of the inadequacy of data on cosmic rays of super-high energies ($E > 10^{15}$ eV; we are referring to the energy spectrum and chemical composition), the electron-positron component spectrum near the Earth and the percentage of positrons in this component, as well as the absence of data on cosmic γ rays (only the upper limit of the flux is known here: Ginzburg and Syrovatsky 1963 a, b, Kraushaar et al. 1965). As for the further investigation of the chemical composition of cosmic rays, the topical problems are well known: determination of the isotopic composition (e.g. the proportion of D and ^{3}He in hydrogen and helium), elucidation of the energy dependence of the composition (in the low energy region we must first of all know the ratio L/S: see Webber 1964, Kurnosova et al. 1965, Badhwar et al. 1965 and below) etc. If the data on the chemical composition and parameters of the fragmentation of nuclei in collisions are made sufficiently accurate, interesting possibilities will open for the choice and specification of various models proposed for describing the movement of cosmic rays in the Galaxy (see Ginzburg and Syrovatsky 1963 b, section 15, and section 4 below).

(iv) On the theoretical plane there are, apart from the problems mentioned above, several other obscurities.

What is the concrete mechanism of accelerating cosmic rays in different cases (outbursts of supernovae, processes in galactic nuclei, acceleration in the Sun and stellar atmospheres)? Little in fact is known here, while both the high effectiveness of the acceleration and the dependence of this effectiveness on the charge and mass of a particle (in particular, the acceleration of electrons is meant) must be explained. Under the same heading comes the problem of the known universality of the acceleration energy spectrum though something has been done in this respect (see Syrovatsky 1961, Ginzburg and Syrovatsky 1963 b, sections 9, 15, as well as section 4 below).

From observations it is known that cosmic rays stay for a rather considerable time within the envelope of supernovae, and at the same time, the magnetic field in the central parts of the envelope (specifically, the Crab nebula) is either strongly regularized or at any rate has a large regularized component. In a regular field the cosmic rays would pass through the Crab nebula with a diameter of the order of 1 parsec within several years, while the actual age of this envelope exceeds 900 years. A similar problem arises with respect to the radio-emitting clouds and areas in radio- and normal galaxies. The keeping of cosmic rays in envelopes or radio-emitting clouds can be explained in the simplest way if it is assumed that on their border there is a strongly turbulized area through which the cosmic rays diffuse only slowly (the alternative is the assumption that along with the regular field component in the envelope and clouds there is a large irregular field component and thus the movement of cosmic rays is strongly impeded throughout the envelope). However, in this case it must be understood why this turbulent envelope arises.

There are indications and considerations (in particular this is in all probability so if the X ray emission of the Crab nebula is bremsstrahlung, see Ginzburg and Syrovatsky 1964 b) pointing to the fact that the acceleration of cosmic rays continues in the Crab nebula and other objects such as the exploded galaxy M82 (see Ginzburg et al. 1965). Now what is the source and mechanism of the acceleration after the explosion of a supernova or galactic nucleus? There is no answer as yet. The same applies to the nature of radiogalaxies and quasars on which we cannot dwell here in detail (see Robinson et al. 1965, Ginzburg and Ozernoy 1964, and papers in Progr. Theor. Phys. (Suppl. No. 31), 1964).

To sum up, there are many unsolved problems. In section 3 below we shall try to demonstrate that some of these problems can, perhaps, be solved by taking into account plasma processes. Several problems (including the as yet unmentioned problem of the non-stationary models of the origin of galactic cosmic rays) will also be discussed in section 4. We shall now discuss the metagalactic cosmic rays and the origin of cosmic rays observed near the Earth.

2. Metagalactic cosmic rays and the origin of cosmic rays observed near the Earth

It seems to us highly probable that the cosmic ray energy density in the Metagalaxy (i.e. for intergalactic space on the average) w_{Mg} is less by several orders than the galactic density

$$w_{Mg} \ll w_G \sim 10^{-12} \text{ erg cm}^{-3}. \quad (3)$$

* As compared with Ginzburg and Syrovatsky (1963 a, b, 1964 a), we have decreased several times the lower limit for U_{cr} and U_e. The value $U_{cr} \sim 10^{40}$ erg sec^{-1} corresponds to the total energy of the cosmic rays in the Galaxy, $W_{cr} \sim 10^{56}$ erg, and the time of escape of these rays out of the system, $T_d \sim 3 \times 10^8$ years $\sim 10^{16}$ sec. Such an estimation seems to us quite permissible (see sections 3 and 4).

† Solar cosmic rays are not considered here.

Speaking in concrete terms, it is most probable that $w_{Mg} \lesssim 10^{-15}$ erg cm^{-3}. Let us enumerate in brief (for details see Ginzburg and Syrovatsky 1963 a, b) the arguments in favour of the validity of the inequality (3).

(i) The kinetic energy density of intergalactic gas is $K = \rho u^2/2 \sim 10^{-14}$ to 10^{-15} erg cm^{-3} ($\rho \sim 10^{-29}$ g cm^{-3}, $u \sim 1$ to 5×10^7 cm sec^{-1}) and the energy density of the metagalactic magnetic field $H_{Mg}^2/8\pi \lesssim 10^{-15}$ erg cm^{-3} ($H_{Mg} \lesssim 10^{-7}$ Oe; see Ginzburg and Syrovatsky 1963 a,b, Ginzburg and Pisareva 1963); or rather even $H_{Mg}^2/8\pi \lesssim 10^{-16}$ to 10^{-17} erg cm^{-3}. At the same time it appears quite difficult and unnatural to suppose that the cosmic ray energy density w_{Mg} essentially exceeds the densities $\rho u^2/2$ and $H_{Mg}^2/8\pi$. Hence we obtain the evaluation $w_{Mg} \lesssim 10^{-15}$ erg $cm^{-3} \ll w_G$.

(ii) We can evaluate the density w_{Mg} of the cosmic rays entering the metagalactic space from normal and radiogalaxies. Thus we obtain the evaluation $w_{Mg} \sim 10^{-16}$ to 10^{-17} erg cm^{-3}. and at any rate we see no possibility, without overstretching the point, of obtaining the values of $w_{Mg} \sim w_G$.

(iii) From radioastronomical data (we mean that there is no appreciable radio emission from intergalactic space) we can draw definite conclusions on the intergalactic magnetic field H_{Mg} and the energy density of the electron component of metagalactic cosmic rays $w_{e,Mg}$. Thus, at $H_{Mg} \sim 3 \times 10^{-8}$ we have $w_{e,Mg} \lesssim 10^{-2}\, w_{e,G} \lesssim 3 \times 10^{-16}$ erg cm^{-3} ($w_{e,G} \lesssim 3 \times 10^{-14}$ is the energy density of the electron component in the Galaxy). Furthermore, there is no reason to assume that the ratio $w_{e,Mg}/w_{Mg} < w_{e,G}/w_G \sim 10^{-2}$. Hence we have $w_{Mg} \lesssim 10^{-14} \ll w_G$.

(iv) The established upper limit of the cosmic γ ray flux (Kraushaar et al. 1965) also makes it possible to estimate the upper value $w_{e,Mg}$. Even assuming that the optical radiation energy density in the Metagalaxy $w_{ph} = 2 \times 10^{-3}$ eVcm^{-3}, we obtain $w_{e,Mg} \lesssim$ (1-3)$10^{-2} w_{e,G}$. It is more probable that $w_{ph} \simeq 5 \times 10^{-3}$ (see Doroshkevich and Novikov 1964)* and thus we have $w_{e,Mg} \lesssim 10^{-2} w_{e,G}$. Hence we obtain for w_{Mg} the same valuation as in (iii). It is more essential, however, that the inequality (directly following from observations)

$$w_{e,Mg} \ll w_{e,G} \tag{3a}$$

contradicts the metagalactic theory of the origin of cosmic rays observed near the Earth. Indeed, the cosmic ray electron component in the Galaxy is primary, i.e. is not created by the nucleon component. Therefore, the observed electron component might have a metagalactic origin only under the condition $w_{e,Mg} \sim w_{e,G}$ (the necessary additional assumption that metagalactic cosmic rays are isotropic is discussed below).

(v) From the data on the cosmic X ray radiation background we can under certain additional assumptions (see section 3) conclude that $w_{Mg} \lesssim 10^{-2} w_G$.

(vi) The value $w_{Mg} \sim 10^{-17}$ to 10^{-15} erg cm^{-3} is by no means small, also if the energy of metagalactic cosmic rays is compared not only with the energies $\rho u^2/2$ and $H^2/8\pi$ in the intergalactic medium but also with the kinetic energy of the random movement of all galaxies.

(vii) In favour of the violation of the inequality (3) and the assumption that $w_{Mg} \sim w_G$ there are no data and indeed no arguments except the possibility of considering in this case the cosmic rays in the Galaxy and other normal galaxies as having a metagalactic origin. However, such a metagalactic theory encounters (apart from all other difficulties) the well-known impedimenta in the explanation of the chemical composition of cosmic rays (the metagalactic cosmic rays produced at the pre-galactic stage of the evolution of the Metagalaxy would probably be poor in heavy elements; as for the galactic cosmic rays, they are most likely insufficient, as indicated in point (ii), for the accumulation of cosmic rays with energy density $w_{Mg} \sim w_G$).

Thus, let us assume that the inequality (3) holds (in particular near the Galaxy) and cosmic rays in metagalactic space are isotropic. In this case it is quite improbable that the cosmic rays observed near the Earth (and in the Galaxy in general) would have, in an appreciable part of them, a metagalactic origin. Indeed, if the inflow of cosmic rays into the Galaxy is approximately stationary, the intensity of cosmic rays is constant along the paths of particles on the strength of Liouville's theorem. Hence it follows*, under the condition of isotropic cosmic rays in both Metagalaxy and Galaxy, that the energy density of metagalactic cosmic rays in the Galaxy $w_{Mg,G} = w_{Mg}$. The same conclusion can readily be drawn from a more elaborate analysis of the movement of particles as they pass from the Metagalaxy (field H_{Mg}) to the region with a galactic field $H_G \gg H_{Mg}$. Taking into account the non-stationary effect (which may involve the non-observance of Liouville's theorem) might somehow violate the equality $w_{Mg,G} = w_{Mg}$. However, under the concrete conditions of the Galaxy (and galaxies in general) we see no ways or conceivable mechanisms which would 'pump' cosmic rays out of metagalactic space into the Galaxy. Therefore, if the condition (3) holds, the only possibility of obtaining a large value $w_{Mg,G} \simeq w_G \sim 10^{-12}$ is connected with the assumption about a sharp anisotropy of cosmic rays in metagalactic space.

Previously (Ginzburg and Syrovatsky 1963 a, b) we expressed an opinion (in particular, in connection with the work by Sciama (1962)) that any essential anisotropy of cosmic rays in metagalactic space is impossible. However, this contention was not confirmed by concrete estimates, and recently there has been proposed a regular metagalactic field model (Pikelner 1965, see also Piddington 1964) in which the assumption that cosmic rays are anisotropic in the Metagalaxy seems at first glance quite permissible†.

Thus the problem of the anisotropy of cosmic rays proves to be very essential and requiring a thorough analysis. In the next section we shall discuss this problem, the conclusion which will be justified being the denial of the possibility of anisotropy. If this conclusion is accepted, the only real possibility of preserving the metagalactic theory of the origin of cosmic rays in the Galaxy is the rejection of the inequality (3) at least in the region near the Galaxy and, more specifically, the assumption that

$$w_{Mg} \simeq w_G \sim 10^{-12} \text{ erg cm}^{-3}. \tag{4}$$

It is this assumption (4) which is known to be made in metagalactic theories. Above we have enumerated arguments against this possibility, at least when the entire metagalactic state is meant. In addition to what has been said above let

* It is not impossible that there is a rather powerful metagalactic radio emission in the range of centimetre and shorter waves (Dicke and Peebles 1965). In this case in the 7.3 cm wave band the radiation temperature T=3.5°K, which corresponds for black body radiation to the energy density w_{ph}=0.7 eV cm^{-3}. In this case metagalactic electrons with energies $E = 10^9$ eV, for example, decrease their energy to one half as a result of Compton losses within 5×10^8 years. The scattering of radiophotons with the average energy $\epsilon = 2.7\, kT = 0.8 \times 10^{-3}$ eV on relativistic electrons leads to X ray emission. Using the data on X ray background observations (see Ginzburg and Syrovatsky 1964 b), we can conclude that $w_{e,Mg} < 10^{-5}$ eV $cm^{-3} \simeq 3 \times 10^{-4}\, w_{e,G}$.

* This conclusion is quite similar to the conclusion which we make concerning the cosmic rays far from the Earth while observing them inside the terrestial magnetosphere.

† In this model, just as in Sciama (1962), cosmic rays, isotropic in a region with field H_G (Galaxy) enter an intergalactic space with a field $H_{Mg} \ll H_G$ with the conservation of the adiabatic invariant $\sin^2\theta/H$ = constant. Therefore, in the Metagalaxy there is a strong anisotropy ($\theta_{max} = (H_{Mg}/H_G)^{1/2}$) and $w_{Mg}/w_G = H_{Mg}/H_G$. At $H_{Mg} \sim 3 \times 10^{-9}$, $H_G \sim 3 \times 10^{-6}$ and $W_G \sim 10^{-12}$ erg cm^{-3}, we have $\theta_{max} \sim 1°$ and $w_{Mg} \sim 10^{-15}$ erg cm^{-3}.

us dwell on the paper (Burbidge and Hoyle 1964) in which the possibility of the fulfilment of the relation (4) is allowed but unfortunately without taking into account our criticism (Ginzburg and Syrovatsky 1963 a, b). Specifically in this paper (Burbidge and Hoyle 1964) it is assumed that cosmic rays enter the Metagalaxy from radiogalaxies, the average energy release in the explosion of radiogalaxies being assumed to be equal to 10^{62} ergs. This value is not justified and seems to us most likely overestimated by 2 or 3 orders. As for the mechanism accepted (Burbidge and Hoyle 1964) for the acceleration of cosmic rays in their collision with 'ejections' (expanding magnetized clouds ejected by radiogalaxies), this mechanism is absolutely ineffective (Ginzburg and Syrovatsky 1965). Indeed, even if the size of ejections of substance in the explosions of galaxies amounts to $l \sim 200$ kps $= 6 \times 10^{23}$ cm (such are the observed sizes of radio-emitting areas in one of the largest radiogalaxies, Centaurus A) and the concentration of radiogalaxies is $N_{rg} \sim 10^{-78}\,\mathrm{cm}^{-3}$, the relativistic particle will experience one collision on the average for $t \simeq (l^2 N_{rg} c)^{-1} \simeq 10^{20}$ sec $\simeq 3 \times 10^{12}$ years. Therefore, any considerable increase of the energy of the metagalactic cosmic rays (as a result of the mechanism under discussion) for the characteristic time of the evolution of the Metagalaxy $T_{Mg} \sim 10^{10}$ years is out of the question.

To be through with the problem of metagalactic cosmic rays, let us sum up what has been said above. If cosmic rays cannot be strongly anisotropic in metagalactic space (in section 3 we give in favour of this conclusion arguments which seem to be quite convincing) the metagalactic theory of the main part of cosmic rays in the Galaxy can only be preserved if the relation $w_{Mg} \sim w_G \sim 10^{-12}$ erg cm^{-3} (see equation (4)) is observed. All available data testify against this possibility and in favour of the inequality (3). However, there is no complete and unconditional certainty that this inequality is valid, especially in respect to the nearest neighbourhood of the Galaxy. The fact is that many of the above considerations actually apply only to the estimate w_{Mg} along the path of the ray (e.g. referring to the metagalactic γ radiation flux, we mean the production of radiation over a path of 5×10^{27} cm corresponding to the photometric radius of the Metagalaxy). Therefore, it is still difficult to reject completely the assumption that $w_{Mg} \sim w_G$ in some neighbourhood of the Galaxy, while on the average for the Metagalaxy $w_{Mg} \ll w_G$. On the other hand, there are no real grounds for this assumption, and indeed it encounters serious objections (Ginzburg and Syrovatsky 1963 a, b).

Further investigations are necessary in such a situation and, of course, taking into account the fundamental importance of this problem. Here mention can be made of radio, gamma and X ray astronomy, the determination and specification of the intergalactic medium parameters and the possibility of more accurate theoretical estimates.

3. Cosmic rays and plasma processes

An understanding of many insufficiently clear problems of cosmic ray astrophysics is, in our opinion, closely linked with taking into account the plasma processes. Of course, the plasma nature of the cosmic medium is well known, and therefore, the contention is sufficiently evident in its general forms: it is contained in Ginzburg and Syrovatsky 1963 b and probably several other sources (see in particular the analysis of some cosmic plasma effects in Tsytovich 1965 a). Here we intend, however, to make more specific remarks, connected with taking into account the beam and other instabilities in rarified plasma, in application to the problem of interest (Ginzburg 1965).

Let us consider for the sake of definiteness this possibility: that outside the Galaxy the magnetic field issues into metagalactic space smoothly (broadening of the field tube) and with no field irregularities, wave fronts, etc. Under such conditions isotropic (or quasi-isotropic) cosmic rays in the Galaxy will move with conservation of the adiabatic invariant and, as indicated above, generate in the Metagalaxy a beam moving practically along the field. However, this case is a classical example when there develops a beam instability. It is essential that the plasma frequencies of the parent (metagalactic) plasma and the beam itself are very high if compared with T_G^{-1} where T_G is the characteristic time of the evolution of the Galaxy or even the radiogalaxy outburst time. Indeed, let us give without any additional comments and using well-known expressions (e.g. Ginzburg 1960) some values for intergalactic plasma with an electron concentration $n \sim 10^{-5}$. In this case the plasma frequency is $\omega_0 = (4\pi n e^2/m)^{1/2} = 5.64 \times 10^4\, n^{1/2}$ and the Debye radius $D = (kT/4\pi n e^2)^{1/2} \simeq 5(T/n)^{1/2} \sim 5 \times 10^5$ cm (at the temperature $T \sim 10^5$ °K). Under the same conditions the number of ion-electron collisions is $\nu = 5.5\, nT^{-3/2} \ln (220\, Tn^{-1/3}) \sim 10^{-11}$ sec. In the field $H_{Mg} \sim 10^{-7}$ the gyrofrequency $\omega_H = eH/mc = 1.76 \times 10^7$ H (< 10 sec^{-1}) and thus $\omega_0^2 >> \omega_H^2$. Even from these figures it is already clear that weakly damping plasma waves ($kD = (2\pi/\lambda)D \ll 1$) may propagate in metagalactic space. Furthermore, even for a cosmic ray beam with a concentration $N_{cr} \sim 10^{-13}$ cm^{-3} (in the Galaxy $N_{cr} \sim 10^{-10}$; the value $N_{cr} \sim 10^{-13}$ corresponds, with the same spectrum, to the density $w_{cr} \sim 10^{-15}$ erg cm^{-3}) the beam plasma frequency is

$$\omega_s = (4\pi e^2 N_{cr} c^2/E)^{1/2} \sim 5 \times 10^4 (N_{cr} m/M)^{1/2} \sim 5 \times 10^{-4}$$

(here the total energy $E \sim Mc^2 \sim 10^9$ eV, which corresponds to the protons yielding the main contribution to w_{cr}). The extreme smallness of the ratio $2\pi/\omega_s T_G \sim 10^4/T_G$ is evident. It is more essential of course that the ratio $1/\gamma T_G$ is also small (where γ is the increment for the plasma oscillations originating because of the beam instability). The value γ for the case under discussion has recently been estimated (Ginzburg and Ozernoy 1965) just for the above values of the parameters* and under the assumption that the spread of velocities in the beam is $v_s \sim c$. In this case $\gamma_{max}^{-1} \sim 30$ years. In fact we have $\gamma_{max} \sim \omega_s^2/\omega_0$, the largest increment corresponding to the waves for which $kc \sim \omega_0$ (for the shortest weakly damping waves we have $kv_T \sim \omega_0$ or $kD \sim 1$, which leads us to the value $\gamma_{min} \sim \omega_s^2 v_T^2/\omega_0 c^2 \sim 10^{-4}\,\gamma_{max}$, $\gamma_{min}^{-1} \sim 3 \times 10^5$ years). If the magnetic field is taken into account, the beam will generate also waves of other types, which may only, at least at the first stage, increase the rate of growth of perturbations in the plasma. Incidentally, if there is no field, the beam instability does not reduce to the generation of only longitudinal waves either.

Furthermore, on the border of the Galaxy (and especially a radiogalaxy) we can expect concentrations N_{cr} by several orders larger than the maximum probable metagalactic value used ($N_{cr} \sim 10^{-13}$).

Thus the impression is that cosmic rays with a sharply anisotropic function of distribution must quickly become isotropized with the growth of the oscillation amplitude. We cannot, unfortunately, draw final conclusions here (at least if only beam instability is considered) since there is no sufficient clarity as to the non-linear phase of the process and there are no data for taking into account the effect on the cosmic ray beams of those waves which are generated by other sources. Let us elaborate on these remarks.

It is usually assumed (and this seems to be valid for a beam of non-relativistic particles) that the development of beam instability leads to a plateau in the velocity distribution of particles (in the unidimensional case the beam is known to be unstable only if there is a certain maximum at $v \neq 0$ in its velocity spectrum; therefore, the instability vanishes as the plateau forms). Plasma waves (their total energy comparable with the primary beam energy) are generated as the plateau takes shape. Apart from the trend to the formation of the plateau there occurs the isotropization of the beam since it is just the anisotropic velocity distribution of par-

* Not to make the account too cumbersome, we shall (apart from the papers already quoted (Tsytovich 1965 a, Ginzburg 1965, Ginzburg and Ozernoy 1965) in which there are also references to many investigations) indicate only a survey (Kadomtsev 1964), concerned specially with the turbulence of plasma as well as papers by Tsytovich and Shapiro (1965) and Tsytovich (1965 b).

ticles that is unstable, and for the particle distribution isotropic over direction, even the presence of a maximum in the energy spectrum (or velocity spectrum) does not lead to instability. From this point of view, for the above relatively very large values of the increment γ for the growth of beam instability, we ought indeed to expect a rapid isotropization of cosmic rays and the trend to the formation of the plateau in their energy distribution. However, such conclusions should not be regarded as inevitable even if the values of γ, obtained in linear approximation, are rather large. The fact is that under certain conditions, especially for relativistic beams, the non-linear interaction of waves may lead to the stabilization of beams (Tsytovich and Shapiro 1965, Tsytovich 1965 b). Physically, this is connected with the repumping, occurring in non-linear approximation, of the beam-generated waves into the non-resonance part of the spectrum in which the waves do not interact directly with the beam (if the phase velocity of the waves is $v_{ph} = \omega/k > c$, such waves cannot evidently be absorbed by the particles of the beam). On the other hand, the isotropization of the beam occurs not only under the action of waves generated by the beam itself but also under the influence of waves (with $v_{ph} < c$) generated by any other sources and present in the area permeated by the cosmic ray beam under consideration. Under the cosmic conditions there are quite a few sources of different waves (beams emitted by stars, drift of cosmic plasma under the influence of the forces of gravitation and magnetic field, etc.). However, we still cannot estimate the intensity of such waves*.

Thus the problem of the effectiveness of the isotropization of cosmic rays as a result of beam instability in isotropic plasma and under the influence of plasma and other waves from other sources is still quite indefinite. This indefiniteness seems to disappear to a considerable extent with respect to cosmic ray beams if we take into account the existence of an as yet unmentioned aperiodic anisotropic instability: anisotropic distribution of particles in a magnetic field is, in general, unstable even if the plasma waves are not taken into account; as a result of this instability the lines of force curve and the field are in fact turbulized. The criterion for anisotropic instability is as follows (there are also instabilities of other type originating in the case of non-observance of the condition (5) as well):

$$w_{cr,\parallel} - \tfrac{1}{2} w_{cr,\perp} > H^2/8\pi \qquad (5)$$

where $w_{cr,\parallel} = (MN_{cr}/2)\overline{v_\parallel^2}$, $w_{cr,\perp} = (MN_{cr}/2)\overline{v_\perp^2}$; $v_\parallel$ and $v_\perp$ are the cosmic ray velocity components parallel and normal to the field respectively (we are using the non-relativistic expression which can hardly lead to an appreciable error since for the main part of the cosmic rays we have $E - Mc^2 \sim Mc^2$).

In the transition of particles from the Galaxy to the Metagalaxy with adiabatic invariant conservation we have, as indicated above, $w_{cr,\parallel} \simeq w_{Mg} \gg w_{cr,\perp}$, and in this case

$$w_{Mg} \simeq \frac{w_G H_{Mg}}{2H_G} \sim \frac{H_{Mg}H_G}{16\pi} \gg \frac{H_{Mg}^2}{8\pi}.$$

* Also, depending on the spectrum of plasma waves and waves of other types, cosmic rays may accelerate (see Tsytovich 1965 a and section 4 of the present paper) or decelerate as a result of the absorption and emission of these waves. Let us note that as a result of the scattering of waves on the particles of cosmic rays, the latter are slowed down under the conditions of interest to us: this process is similar to the magnetic bremsstrahlung and Compton energy losses. In this case we have $dE/dt = -bw_pE^2$ where b is the same coefficient as for magnetic bremsstrahlung and Compton losses (Ginzburg and Syrovatsky 1963 a, b), and w_p is the energy density of the waves in plasma. Since it seems that we always have $H^2/8\pi \gg w_p$ in the cases of interest to us, the magnetic losses are more essential than the losses in the scattering on plasma waves.

Thus, the criterion (5) will be fulfilled with a large margin (e.g. at $H_{Mg} \sim 3 \times 10^{-8}$ we have $w_{Mg} \sim 3 \times 10^{-15}$ and $H_{Mg}/8\pi \sim 3 \times 10^{-17}$. The increment of the field perturbations under discussion is

$$\gamma \sim \left(\frac{w_{Mg} - H^2/8\pi}{MN_{cr}}\right)^{1/2} k \sim ck$$

since $w_{Mg} \sim N_{cr}Mc^2$. Also, the perturbation wavelength must exceed the cosmic ray gyroradius $r_H \sim Mc^2/eH \sim 3 \times 10^6/H_{Mg} \sim 10^{14}$ cm (at $H_{Mg} \sim 3 \times 10^{-8}$). Consequently we have $\gamma \lesssim 2\pi c/r_H \sim 10^{-3}$ and $\gamma_{max}^{-1} \sim 10^3$ sec! The plasma waves originating as a result of the beam instability discussed earlier may apparently only accelerate the turbulization of the field and isotropization of the beam.

Thus it is evident that if the cosmic ray beam reached the metagalactic region (the region where $H \sim H_{Mg} \sim 3 \times 10^{-8}$) without isotropization and without destruction of the regular structure accepted above for the basis, both processes would be very rapid. Now, this means that the regular picture of the broadening of field tubes is not real under such conditions and actually there must form a transitional area in which the field will be turbulent even if it were regular in the Galaxy, and the cosmic ray beam will become isotropic. Thus, if a large new portion of cosmic rays orginates somewhere in the Galaxy (say, as a result of the outburst of a galactic nucleus), these cosmic rays become 'self-isolated' quite rapidly; they surround the area they occupy by a turbulent layer, preventing the rapid flow of cosmic rays into the environmental space with a weak field*.

This is why, from the point of view under discussion, we observe in radiogalaxies radio-emitting clouds and not simply the spread of cosmic rays along the lines of the field. Of course, these 'clouds' containing isotropic cosmic rays may expand and move as a whole, which is just what is observed. Besides, a certain diffusion outflow of cosmic rays is also possible if there is a turbulent layer restricting the system (the Galaxy, 'clouds' in radiogalaxies, supernovae shells).

Unfortunately, no reliable estimate of the diffusion coefficient D through the above turbulent layer is possible without elaborating the picture, taking into account all essential instabilities, non-linear interaction of waves, etc. (Kadomtsev 1964). As a minimum value of D we can apparently consider the value

$$D_{min} \sim \frac{r_H c}{3} \sim \frac{Mc^3}{3eH} \sim \frac{3 \times 10^{16}}{H}$$

(we mean particles with energies $E \sim Mc^2$). The value $D_{min} \sim 10^{22}$ cm^2 sec^{-1} thus obtained for the Galaxy (at $H_G \sim 3 \times 10^{-6}$) is considerably smaller than the coefficient $D \sim 10^{28}$ to 10^{29} used by Ginzburg and Syrovatsky (1963 b). However, there is no contradiction here since in the turbulent region the field is weaker than in the Galaxy as a whole, while the coefficient D may yet be essentially larger than D_{min}.

Anyway, the appearance of a turbulent layer in the area of transition from a strong to a weak field is no doubt a favourable circumstance for explaining the holding of cosmic rays within the envelopes of supernovae, the Galaxy and in radio-emitting areas (clouds) in radiogalaxies. In particular, in application to the Galaxy we can assume that the characteristic time of outflow of cosmic rays from the system is $T_d \sim 3 \times 10^8$ years since this value does not yet contradict the

* In case of the outflow of cosmic rays through the arm of the galactic helix, from the point of view under discussion, we can refer to the production of turbulent stoppers (mirrors) preventing the outflow of cosmic rays from the arm. Of course, a turbulent layer is formed gradually and some part of the cosmic rays escapes from the system without any special obstacle.

data on the chemical composition of cosmic rays (see section 4).

We have seen that as a result of the joint action of different mechanisms of the instability of the anisotropic distribution of particles there are grounds to expect that the cosmic rays will become effectively isotropic; while this process is in operation smoothing of the energy distribution functions also occurs*.

On the strength of the above it can be supposed that the cosmic rays getting into intergalactic space from the galaxies will be isotropized rapidly in the transitional area near the galactic boundaries. For this reason alone (let alone the possibility of isotropization in metagalactic space itself) metagalactic cosmic rays must be practically isotropic just as was supposed at the end of section 2.

The isotropization of cosmic rays generated in, say, the outburst of galactic nuclei and being at some stage sharply anisotropic (this is always the case in the regular influx of cosmic rays into the region with a weaker regular field) is accompanied by the generation of waves of different types. The total energy passing into these waves (in particular, plasma waves) is probably of the same order as the total energy of the cosmic rays generated. Propagating in metagalactic space, the waves heat intergalactic gas as a result of collisions. The heating of the gas also occurs effectively as a result of ionization losses of sub-cosmic rays (particles with energies $E < 10^8$ eV) the generation of which is quite probable. Calculations (Ginzburg and Ozernoy 1965) lead to the conclusion that, roughly, we have $nkT \sim w_{Mg} + w_{scr}$ (here T is the temperature of the intergalactic gas with a concentration n, and w_{Mg} and w_{scr} are the energy densities of cosmic and sub-cosmic rays in metagalactic space). Therefore at $n \sim 10^{-5}$ and $w_{Mg} + w_{scr} \sim 10^{-15}$-$10^{-16}$ the temperature $T \sim (w_{Mg} + w_{scr})/kn \sim 10^5$-$10^6$ °K. Thus, in the framework of evolutionary cosmology (this is the assumption on which the calculations (Ginzburg and Ozernoy 1965) were based) the temperature of the intergalactic medium may and probably must be high, despite the cooling due to the general expansion of the Metagalaxy. In terms of the present report another conclusion is more essential: if the condition (4) were observed, i.e. the energy density w_{Mg} were of the order $w_G \sim 10^{-12}$, the cosmic rays being supplied by galaxies and radiogalaxies (as is usually assumed in the metagalactic theories of the origin of cosmic rays, see Burbidge and Hoyle 1964) we could expect the heating of the intergalactic gas to the temperature $T \sim w_G/kn \sim 10^9$ °K. However, from the data on the cosmic X ray radiation background it follows (Gould and Burbidge 1963, Field and Henry 1964) that the temperature $T < 3 \times 10^6$ (if the estimate $T \sim w_{Mg}/kn$ is used we have $w_{Mg} < 3 \times 10^{-15}$ erg cm^{-3}). X ray background measurements for wavelengths reaching 50 Å will make it possible to specify the value T if it is not smaller than 4×10^5 °K (see Gould and Sciama 1964). The use of the estimate $T \sim w_{Mg}/kn$ and X ray data involves, of course, some additional assumptions. There is no doubt, however, that along these lines we obtain an additional argument in favour of the validity of the inequality $w_{Mg} \ll w_G \sim 10^{-12}$.

Taking into account the plasma effects in cosmic ray astrophysics is merely a beginning and involves considerable difficulties. Therefore, some of the above considerations have not been sufficiently developed and we must rather refer to surmises and a programme for research than to quite definite conclusions. Nevertheless in our opinion there is every reason to believe that the analysis of plasma processes is of fundamental importance for the further development of cosmic ray astrophysics*.

4. Remarks concerning some problems of cosmic ray astrophysics

This section contains several remarks concerning the problems with respect to which we either cannot give more space within the scope of this report or there are still very few data.

One of such problems of cardinal importance not only for cosmic ray astrophysics but also for the theory of solar flares and radiation belts is the acceleration of particles to high energies. It is known (Ginzburg and Syrovatsky 1963 b) that the statistical mechanism of acceleration (Fermi mechanism) in application to interstellar space proves ineffective if the available data on the velocity and size of the characteristic irregularities (clouds) in an interstellar medium are used. Also, the assumption of the interstellar acceleration of cosmic rays involves energetic difficulties. Therefore, in the galactic theory of the origin of cosmic rays supernovae and flares of galactic nuclei are regarded as main sources. At the same time the problem of interstellar acceleration (or additional acceleration) cannot as yet be regarded as completely clarified. Thus, in the presence in interstellar space of plasma and other waves with sufficiently high (but still small compared with the thermal energy of the medium) energy density, the interstellar acceleration may prove effective (Tsytovich 1965 a). This supposition deserves attention. However, the sources of such waves, the power they transfer, maximum energy and maximum energy density of particles remain for the time being problems yet to be solved.

Let us note furthermore that in the case of an interstellar acceleration throughout the volume occupied by cosmic rays the thickness of the substance they pass through will increase with energy. We shall see below that experimental data do not support this possibility.

Thus even when the plasma effects are taken into account there is no ground to give up the supposition that the main sources of cosmic rays in the Galaxy are supernova outbursts and perhaps outbursts of galactic nuclei.

The acceleration mechanism in these explosive processes is not yet sufficiently clear. In principle it is possible that here we have an effective regular or statistical acceleration in turbulent magnetic fields. However, the investigation of solar flares which perhaps (at least partially) simulate the processes at work in the outbursts of supernovae and in radiogalaxies indicates that the probable particle acceleration mechanism is the direct conversion of magnetic energy into the energy of fast particles under the conditions when the 'frozen-in' state of the magnetic field is violated. A possible mechanism of this acceleration is considered by Syrovatsky (1965). The investigation of the generation of fast particles in solar flares seems now the most promising way for elucidating the nature of cosmic accelerator mechanisms since in this case we can obtain much richer information than for remote sources.

Energetically, the generation of cosmic rays in supernova outbursts does not, in our view, involve any serious difficulties. In addition to what was said in section 1 it should be noted that as a result of the new estimation of the distances (Woltjer 1964) the power of supernovae of the first type proves to be essentially larger than was supposed by Ginzburg and Syrovatsky (1964 b) and becomes of the same order as the power of supernovae of the second type. As a result the energy of cosmic rays contained in the envelopes of supernovae of the first and second types proves to be to one

* We are not concerned here with solar cosmic rays since rapid processes are essential in this case and it is possible that isotropy cannot advance sufficiently far. However, the above remarks must also be taken into account in the analysis of the problem of solar cosmic rays.

* After this report had been written we read a preprint of a paper by E. Parker (Parker 1965) and we are glad to state the proximity of the views of Dr. Parker's and ours concerning several topical problems of cosmic ray astrophysics. However, we had no time to give due credit to Dr. Parker's investigations in our report.

order of magnitude equal to 3×10^{49} ergs. Now, the total energy of cosmic rays generated as a result of an outburst may and perhaps must be much higher since the system keeps losing cosmic rays all the time. The upper limit of the total energy of cosmic rays is of the order of the total energy of the outburst, coming up to 10^{51} to 10^{52} ergs. Yet even if the maximum value for the power of injection $U_{cr} \sim 10^{41}$ erg sec^{-1} (see equation (2)) is used with the minimum estimate for the outburst frequency in the Galaxy (one outburst per 300 years) a value of 10^{51} ergs per outburst in the transition in the cosmic rays is obtained. In terms of the galactic theory of the origin of cosmic rays observed near the Earth we have also as 'standby' sources the outbursts of the galactic nucleus the contribution of which is still unknown (for details see Ginzburg and Syrovatsky 1963 a, b, 1964 a, Robinson et al. 1965; papers in Progr. Theor. Phys. (Suppl. No. 31), 1964, and the references in these papers). It should be noted that in the case of rare and powerful outbursts of the nucleus we would deal with a non-stationary galactic theory of the origin of cosmic rays (Ginzburg and Syrovatsky 1963 a, b, 1965, A. Charakhtchyan and T. Charakhtchyan 1964). For the time being we see no direct arguments in favour of this alternative; however, some possibilities can be indicated for checking the non-stationary model (see below).

Of major interest is the problem of the energy spectrum of cosmic rays and their radio-emitting electron component. Kellermann (1964) established that the spectral indexes of radio emission of extragalactic objects with low dispersion group near the value $\alpha = 0.76$. This is interpreted sometimes as an indication of the existence of one integral reservoir of cosmic rays (the Metagalaxy is meant) whence cosmic rays get into the galaxies and hence have the same energy spectrum everywhere. In addition to what was said in section 2 concerning the difficulties of the metagalactic theory of the origin of cosmic rays it should be noted that there is no need for the assumption of the existence of such an integral reservoir. The fact is that under the conditions of the 'equidistribution' of energy between cosmic rays, turbulence and magnetic field (see (1)), the spectrum of cosmic rays emanating from the sources (supernovae, the region of the galactic nucleus) has a universal value (Syrovatsky 1961, Ginzburg and Syrovatsky 1963 b) $\gamma = 2\alpha + 1 = 2.5$. In this case no restrictions are imposed on the spectrum in the sources themselves: this spectrum may be arbitrary. The latter agrees with measurements (Kellermann 1964) indicating that the spectral indexes of the galactic sources have an essentially larger dispersion than those of the extragalactic sources (the Crab nebula with the radio index $\alpha \simeq 0.25$ is a characteristic example).

Let us now dwell briefly on the chemical composition of cosmic rays the investigation of which may furnish much information on the sources, the type of acceleration and propagation of cosmic rays. The average thickness of matter travelled by cosmic rays in their movement in the Galaxy is known to be determined fairly reliably (2 to 10 g cm^{-2} depending on the accepted parameters and the propagation model) as is the composition in the sources. As the data on the composition and parameters of fragmentation become more accurate it will be possible to make the proper choice of the propagation model (first of all between the regular and diffusion models) (Ginzburg and Syrovatsky 1963 b) and to determine the age of cosmic rays and the average density of substance in the region of their propagation (Durgaprasad 1964, Theses, Tata Inst. of Fundamental Research), the character and duration of acceleration (Badhwar et al. 1965, Kristiansson 1964, Badhwar and Daniel 1963) as well as the dependence of the thickness travelled and the diffusion coefficient of energy (Badhwar et al. 1965, Appa Rao 1964).

The available data on the chemical composition can hardly be brought into agreement (Ginzburg and Syrovatsky 1965) with the above hypothesis on the powerful and rare outbursts in the galactic nucleus area leading to the production in one such outburst of the bulk of cosmic rays (non-stationary galactic model). Indeed, in this model, the particles have passed through the thickness $x = \rho vt$ g cm^{-2} in the time t after the outburst, where ρ is the average density of matter in the region of cosmic ray propagation, and v is the cosmic ray velocity. Hence it follows that non-relativistic particles ($v < c$) must, by the moment of observation, have passed through a smaller thickness of matter than relativistic particles ($v \simeq c$). However, from the data on the chemical composition it follows that for non-relativistic energies the proportion of L nuclei (Li, Be and B) is higher (Kurnosova et al. 1965, Badhwar et al. 1965, Apparao 1964) than for relativistic energies. This evidently corresponds to a larger thickness of matter passed by non-relativistic particles, which would contradict the non-stationary model. More rigorous conclusions can only be made after taking into account the ionization losses and the character of particle propagation in relation to energy (it is not impossible that slow cosmic rays move in the main in the area of the disk where the average density is higher while relativistic particles spend a considerable part of time in the more rarified halo).

Also, the non-stationary model can be checked by investigating the relative amount of L nuclei, ^{3}He and D in relativistic cosmic rays (Kuzhevsky and Syrovatsky 1965).

The problem of the nature of the electron component of cosmic rays has been clarified to a considerable extent. According to calculations (Ginzburg and Syrovatsky 1964 a, see also section 17 of the English edition of Ginzburg and Syrovatsky 1963 b) radio-emitting electrons in the Galaxy cannot have a secondary origin but must be generated directly in the sources, just as the proton-nuclear component. This conclusion is in agreement with the results of measurements of the proportion of positrons in the composition of the electron component of cosmic rays (De Shong et al. 1964). Of special importance now is the measurement of the electron spectrum in the energy region $E > 3$ to 10 GeV which cannot be evaluated at least at present by radioastronomical data.

Let us finally dwell briefly on gamma and X ray astronomy in its connection with cosmic ray astrophysics (for more detail see Ginzburg and Syrovatsky 1964 b). The possibility of estimating the concentration of relativistic electrons in the Metagalaxy proceeding from the intensity of Compton gamma rays makes gamma astronomy an indispensable means for investigating cosmic rays in the Metagalaxy (see section 2).

With respect to discrete gamma ray sources it seems interesting to realize the possibility indicated by Ginzburg et al. (1964) (see also Robinson et al. 1965) for registering gamma rays from the quasar radio source 3C273 B generated by reason of the Compton scattering of optical photons on relativistic electrons in this source. In connection with new data (Low and Johnson 1965) on the emission of the object 3C273 B in the infra-red region and the corresponding increase of the total luminosity of this object, the expected gamma ray flux may even be higher than the estimate obtained by Ginzburg et al. (1964) $F_\gamma(E_\gamma > 3\ \text{MeV}) \simeq 5 \times 10^{-6}$ photons cm^{-2} sec^{-1}. The usual galaxies are not anomalously strong gamma emitters. This applied (Ginzburg et al. 1965) also to the M82 galaxy in which outbursts of the nucleus are observed.

In X ray astronomy the initial optimism inspired by the hope of observing hot neutron stars has now waned. The reasons are, first, the large size of the X ray source in the Crab nebula (Bowyer et al. 1964) and, second, the elucidation of the fact that neutron stars cool (if accretion is not taken into account (Zeldovich and Novikov 1965)) perhaps much more quickly (Ginzburg and Kirzhnits 1964, Bahcall and Wolf 1965) than was supposed before. The discovery of the X ray emission of neutron stars cannot, of course, be ruled out, but it is more probable that not only the Crab nebula but other observed cosmic sources of X rays are not neutron stars either. It is most probable that the X ray emission of these sources has a magnetic bremsstrahlung nature (Ginzburg and Syrovatsky 1964 b, Woltjer 1964). Nevertheless, the thermal bremsstrahlung mechanism of cosmic X ray emission is not yet ruled out (Burbidge et al. 1965, Morrison and Sartori 1965). Under such conditions the most convincing argument in favour of the magnetic bremsstrahlung character of X ray emission would be the discovery of its polarization (complicated though they are, such polarization measurements are possible in principle).

Less than two years intervene between this report and its predecessor (Ginzburg and Syrovatsky 1963 a). Nevertheless, apart from progress made in several sectors of theory and experiment, the exceptional role of cosmic rays in astrophysics has become especially clear.

References

Apparao, M. V. K., 1964, Nuovo Cim., **32**, 1158.

Badhwar, G. D., and Daniel, R. R., 1963, Progr. Theor. Phys., **30**, 615.

Badhwar, G. D., Devanathan, S. N., and Kaplon, M. F., 1965, J. Geophys. Res., **70**, 1005.

Bahcall, J. V., and Wolf, R. A., 1965, Phys. Rev. Letters, **14**, 343.

Bowyer, S., Byram, S. T., Chubb, T. A., and Friedman, H., 1964, Science, **146**, 912.

Burbidge, G. R., Gould, R. J., and Tucker, W. H., 1965, Phys. Rev. Letters, **14**, 289.

Burbidge, G. R., and Hoyle, F., 1964, Proc. Phys. Soc., **84**, 141.

Charakhtchyan, A. N., and Charakhtchyan, T. N., 1964, Geomagnetism i Aeronomia, **4**, 643.

De Shong, J. A., Hildebrand, R. H., and Meyer, P., 1964, Phys. Rev. Letters, **12**, 3.

Dicke, R. H., and Peebles, P. Y., 1965, Space Sci. Rev., **4**, 419.

Dorman, I. V., and Dorman, L. I., 1965, Geomagnetism i Aeronomia, **5**, 666.

Doroshkevich, A. G., and Novikov, I. D., 1964, Dokl. Akad. Nauk SSSR, **154**, 809.

Field, G. R., and Henry, R. O., 1964, Astrophys. J., **140**, 1002.

Ginzburg, V. L., 1960, Propagation of Electromagnetic Waves in Plasmas (Fizmatgiz, Moscow; English translation Pergamon Press (1964)).

——— 1965, Astr. Zh., **42**, No. 6 (preprint of the P. N. Lebedev Physical Institute A-48).

Ginzburg, V. L., and Kirzhnits, D. A., 1964, Zh. Eksper. Teor. Fiz., **47**, 2006.

Ginzburg, V. L., and Ozernoy, L. M., 1964, Zh. Eksper. Teor. Fiz., **47**, 1030.

——— 1965, Astr. Zh., **42**, No. 5 (preprint of the P. N. Lebedev Physical Institute A-41).

Ginzburg, V. I., Ozernoy, L. M., and Syrovatsky, S. I., 1964, Dokl. Akad. Nauk SSSR, **154**, 557.

——— 1965, Izv. Akad. Nauk SSSR, Ser. Fiz., **29**, No. 10.

Ginzburg, V. L., and Pisareva, V. V., 1963, Radiofizika (Izvestia Vuzov), **6**, 877.

Ginzburg, V. L., and Syrovatsky, S. I., 1963 a, Proc. Int. Conf. Cosmic Rays, Jaipur, **3**, 301.

——— 1963 b, The Origin of Cosmic Rays (Moscow: Academy of Sciences Publishing House; English edition Pergamon Press (1964)).

——— 1964 a, Astr. Zh., **41**, 430; Soviet Astronomy AJ, **8**, 342.

——— 1964 b, Usp. Fiz. Nauk, **84**, 201; Dokl. Akad. Nauk SSSR, **158**, 808; see also 1965, Space Sci. Rev., **4**, 267.

——— 1965, Izv. Akad. Nauk SSSR, Ser. Fiz., **29**, No. 10.

Gould, R. F., and Burbidge, G. R., 1963, Astrophys. J., **138**, 969.

Gould, R. J., and Sciama, D. W., 1964, Astrophys. J., **140**, 1634.

Kadomtsev, B. B., 1964, Voprosy Fiziki Plazmy, issue 4 (Moscow: Atomizdat).

Kellermann, K. I., 1964, Astrophys. J., **140**, 969.

Kraushaar, W., et al., 1965, Astrophys. J., **141**, 845; see also Garmire, G., and Kraushaar, W. K., 1965, Space Sci. Rev., **4**, 123.

Kristiansson, K., 1964, Ark. Phys., **25**, 513.

Kurnosova, L. V., Razorenov, L. A., and Fradkin, M. I., 1965, Izv. Akad. Nauk SSSR, Ser. Fiz., **29**, No. 10.

Kuzhevsky, B. M., and Syrovatsky, S. I., 1965, Zh. Eksper. Teor. Fiz., **49**, No. 12.

Low, F. J., and Johnson, H. L., 1965, Astrophys. J., **141**, 336.

Morrison, P., and Sartori, L., 1965, Phys. Rev. Letters, **14**, 771.

Parker, E. N., 1965, The Dynamical Properties of Cosmic Rays, in the press.

Piddington, J. H., 1964, Mon. Not. R. Astr. Soc., **128**, 345.

Pikelner, S. B., 1965, Astr. Zh., **42**, 515.

Robinson, I., Schild, A., and Schuckling, E. L., Eds, 1965, Quasi-stellar Sources and Gravitational Collapse (Chicago: University of Chicago Press).

Sciama, D., 1962, Mon. Not. R. Astr. Soc. **123**, 317.

Syrovatsky, S. I., 1961. Zh. Eksper. Teor. Fiz., **40**, 1788; Soviet Physics-JETP, **13**, 1257.

——— 1965, Zh. Eksper. Teor. Fiz., in the press.

Tsytovich, V. N., 1965 a, Astr. Zh., **42**, 33.

——— 1965 b, Preprint of the P. N. Lebedev Physical Institute.

Tsytovich, V. N., and Shapiro, V. D., 1965, Yaderny Sintez (Nuclear Fusion), **5**, No. 3.

Webber, W. R., 1964, Handb. d. Phys. 46/2 (Berlin: Springer-Verlag).

Woltjer, L., 1964, Astrophys. J., **140**, 1309.

Zeldovich, Ya. B., and Novikov, I. D., 1965, Usp. Fiz. Nauk, **84**, 377; **86**, 447.

Discussion

T. GOLD. Do you know any cause against supposing that there is a rather strong magnetic field between the galaxies, much stronger than would result from equipartition with any form of energy there? I appreciate that we do not know how it is generated, but we also do not know how the matter was there. The large scale field may well be a cosmological problem just as the presence of the matter.

S. I. SYROVATSKY. From the theoretical point of view, I do not see any reason for such an assumption. Besides, the measurements of intensity of background radio emission and the Faraday rotation of the plane of polarization for remote sources puts the upper limit for the metagalactic magnetic field $H \leqslant 10^{-7}$ gauss

T. GOLD. If the gas density is assumed low enough then the limits imposed by these considerations on the magnetic field strength are raised to such values that the magnetic pressure could be really significant for galactic gas dynamics, that is 10^{-12} or 10^{-13} dyn cm^{-2}.