THE COSMIC-RAY HALO:
INSIGHT FROM GAMMA RAYS AND COSMIC-RAY OBSERVATIONS

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ABSTRACT. The physical processes that determine the size of the galactic cosmic-ray halo are discussed and observational information on the cosmic-ray halo is summarized. Based on theoretical investigations as well as observations, we conclude that the halo surrounding the galactic disk is extensive and that its extent in the direction perpendicular to the galactic plane is more than 10 kpc.

1. INTRODUCTION

A halo is generally defined as a quasi-spherical or even substantially flattened region surrounding the galactic disk of a spiral galaxy (see Figure 1). One can speak of many different halos, namely: the stellar halo, gaseous halo, cosmic ray halo, magnetic halo, radio halo, gamma-ray halo, and even the invisible (dark matter) halo (see for instance Ginzburg, 1988). All these halos can be absolutely different in their parameters, which are determined by different physical processes. On the other hand, these processes are not completely independent and very often influence each other. So, we have a complex situation with connections and interactions of halos of different types. In the following we shall mainly discuss the origin of the cosmic-ray halo and its different manifestations in observational data.

Historically, the first evidence for the existence of the galactic cosmic-ray halo came from radio observations. Measurements of the diffuse radio emission showed that its distribution on the sky is anisotropic, but the intensity of the radio emission does not significantly vary for directions perpendicular to the galactic plane. From this one may conclude that a considerable part of the radio flux is generated inside our Galaxy, but the radio emitting region is not limited to the galactic disk. Schklovskii (1952) proposed that the radio emission is generated in a quasi-spherical halo-type volume. However, he connected this radio halo to the stellar halo, suggesting that the radio emission is generated by hypothetic "radio stars" filling the halo region. Soon it became clear that the "radiostar" hypothesis is

H. Bloemen (ed.), The Interstellar Disk-Halo Connection in Galaxies, 175–186.

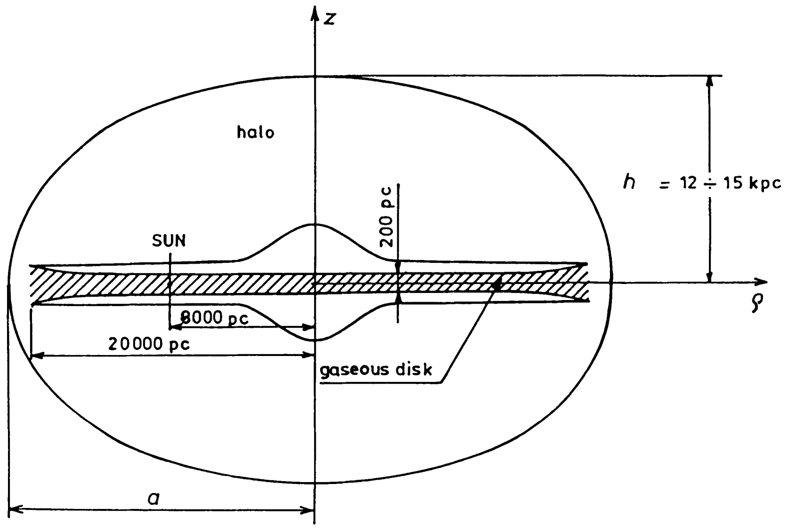

Figure 1. Schematic view of the galactic stellar and gaseous disks and the halo. The Sun is assumed to be at a distance of $\rho_\odot = 8$ kpc from the galactic centre.

invalid and that the observed radio emission is of synchrotron nature, i.e., is generated by relativistic cosmic-ray electrons propagating in the magnetic fields of the halo (Ginzburg, 1953). This was the first time the cosmic-ray halo was mentioned.

2. PHYSICAL GROUNDS FOR THE EXISTENCE OF A COSMIC RAY HALO

The existence of a cosmic-ray halo is expected on physical grounds. One can imagine the interstellar medium of the galactic disk as a mixture of thermal gas, magnetic fields and cosmic rays, with similar energy densities for each of these components. In such a scenario, confinement of cosmic rays inside the disk seems highly improbable, even if all cosmic-ray sources are located inside the disk. Indeed, both theoretical and experimental plasma studies testify to the fact that even in regular magnetic fields (of a special configuration), a plasma develops various instabilities and flows out of the traps. So there seems to be no doubt that cosmic rays flow out of the gas disk and fill up a more extended region. In this scenario, the cosmic-ray halo is an extended region surrounding the gas and stellar disks, filled with cosmic rays and magnetic fields.

Very often the existence of the cosmic-ray halo is connected to the development of so-called Parker instabilities (see, for example, Parker, 1966; Cesarsky, 1980; Kuznetsov and Ptuskin, 1983), which occur in a disk filled with a thermal gas, magnetic fields and cosmic rays. The equilibrium condition in the direction perpendicular to this disk is

$$\frac{\partial}{\partial z}\left(P_g + P_{cr} + \frac{H_o^2}{8\pi} + \frac{H_t^2}{24\pi}\right) = -\rho(z)g(z), \qquad (1)$$

where P_g is the gas pressure, P_{cr} the cosmic-ray pressure, ρ the gas density distribution, g the gravitational acceleration determined by the stellar disk, and H_o and H_t the regular and turbulent components of the interstellar magnetic fields.

The equilibrium state described by eq. (1) can be unstable due to the excitation of Rayleigh-Taylor instabilities, which leads to a situation in which an initially small curvature of a magnetic-field line is increased. As a result, large loops of magnetic fields, filled with cosmic rays, are generated. They may extend far above the galactic plane, with characteristic scales as large as several kiloparsecs.

The characteristics of cosmic-ray propagation are determined by the scattering of cosmic rays on small-scale magnetic-field fluctuations. The interaction of cosmic rays with such fluctuations can be described by a typical scattering frequency $\nu(r, E)$, where r is a space coordinate and E is the particle energy. It is realistic to suppose that the value of ν decreases sufficiently far away from the galactic disk. The kinetic equation for the cosmic-ray distribution function f is of the form (for more details see Dogiel et al., 1990)

$$\frac{\partial f}{\partial t} + v\frac{\partial f}{\partial r} = I(f) + Q(r, E), \tag{2}$$

where v is the particle velocity, $Q(r, E)$ is the distribution of cosmic-ray sources and $I(f)$ is the integral of particle collisions with magnetic inhomogeneities

$$I(f) = \nu(r, E)\frac{\partial}{\partial p_i}\left\{(\delta_{ik}p^2 - p_i p_k)\frac{\partial f}{\partial p_k}\right\}, \tag{3}$$

where p is the particle momentum.

The problem is characterized by the dimensionless parameter

$$\delta = \frac{\nu(r, E)\ell(r)}{v} \qquad \left(\ell = f/\frac{\partial f}{\partial r}\right). \tag{4}$$

The condition $\delta = 1$ determines the boundary $r = \bar{r}$, at which the character of particle propagation changes drastically.

In the inner region, $r \ll \bar{r}$ ($\delta \gg 1$), the distribution function f is quasi-isotropic and particle propagation is described by the diffusion equation with a diffusion coefficient $D \simeq c^2/\nu(r, E)$.

In the outer region, $r \gg \bar{r}$ ($\delta \ll 1$), the function f is highly anisotropic, because particle scattering is not effective there.

The average velocity of the flux of relativistic particles ($v \simeq c$), ejected in the central part of the system, increases at the boundary $r = \bar{r}$ from the value $u = D/\ell \ll c$ (for $r \ll \bar{r}$) to the value $u = c$ (for $r \gg \bar{r}$). So cosmic rays spend a relatively long time in the volume $r \ll \bar{r}$ (where particle scattering is effective), before escaping from the boundary at $r = \bar{r}$ to the metagalactic space.

We shall consider the volume bounded by the surface $r = \bar{r}$ as the cosmic-ray halo. It follows from eq. (4) that the scale height of the halo may a function of the particle energy, $\bar{r} = \bar{r}(E)$.

This type of halo, where particles are diffusively propagating along magnetic field lines, is usually called a "static halo". Another type of halo, "dynamic (convective) halo", in which cosmic rays are transported by a galactic wind with magnetohydrodynamic velocity $u \ll c$, is also probable for our Galaxy (Bulanov et al., 1972, Lerche and Schlickeiser, 1982). This wind is caused by the outward flux of MHD-waves and, according to Breitschwerdt et al. (1987), does probably occur at the periphery of the galactic halo (at a distance of several kiloparsecs from the galactic plane).

The cosmic-ray transport equation, that gives the cosmic-ray density for both halo types, is of the form (see Berezinsky et al., 1990)

$$\nabla(D(\nabla f) - uf) + \frac{\partial}{\partial E}(b(E)f) = Q(r, E), \tag{5}$$

where $b(E)$ is the rate of continuous energy losses.

It can be seen from Eq. (5) that the halo parameters may be different for different components of cosmic rays due to the continuous loss term. We remind the reader that we consider the cosmic-ray halo as a region surrounding the disk, in which the cosmic-ray density is significantly higher than in the intergalactic medium. Speaking of the cosmic-ray halo, it is most reasonable to refer to stable components of cosmic rays. These particles have the largest halo size. For heavy elements (starting from iron), for radioactive elements with a relatively small lifetime (Be^{10} and others), and for electrons which are under the influence of continuous energy losses, the halo scale height will be smaller and, generally speaking, energy dependent.

3. THE HALO OF COSMIC-RAY ELECTRONS AND THE RADIO HALO

As mentioned in the Introduction, the halo of cosmic-ray electrons (or the radio halo, connected with it) was discovered as early as 1952-53. However, the existence of this halo was still doubtful for a long time. There were several reasons for this. First of all it is very difficult to investigate the radio halo of our Galaxy, because we are inside and it is very hard to distinguish between local, metagalactic and halo components of radio emission. Secondly, the attempts to observe radio halos of other spiral galaxies were unsuccessful (see for instance van Woerden , 1967).

Nevertheless, good estimates of the radio flux generated by the cosmic-ray halo could be obtained if a reasonable cosmic-ray electron distribution in the Galaxy could be calculated in the framework of a model with a minimal number of free parameters. This is the case for the diffusion model discussed above (eq. 5). The intensity of the radio emission in a direction ℓ is given by

$$J_\ell(\nu) = \int_\ell d\ell \int_E P(E, \nu) f_e(E, r) dE, \tag{6}$$

where $P(E, \nu)$ is the intensity of synchrotron radiation emitted by a single electron with energy E at a frequency ν and $f_e(E, r)$ is the electron distribution calculated from eq. (5).

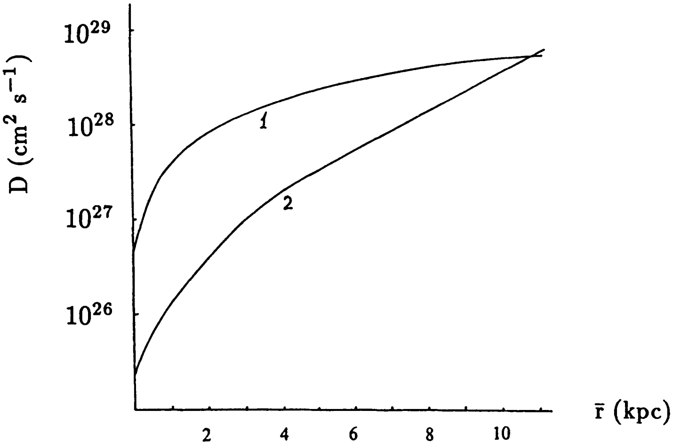

Figure 2. Dependencies of the diffusion coefficient D on the halo extent $\bar{r}$:
(1) obtained from cosmic-ray electron data and diffuse radio emission;
(2) determined from the chemical composition of cosmic rays.

It follows from eq. (5) that electrons with large energies fill only part of the cosmic-ray halo, because of the extensive energy losses. Their path length $\lambda(E)$, determined from the equation

$$\lambda^2(E) = \int_{E_o}^{E} \frac{D(E')}{b(E')} dE' \tag{7}$$

(E_o is the initial energy of an electron), is smaller than the extent of the cosmic-ray halo, $\bar{r}$ ($\lambda(E) < \bar{r}$). As a result, the size of the cosmic-ray electron halo is energy dependent. Correspondingly, the scale height of the radio halo depends on the radio frequency.

The analysis of the observed diffuse radio emission, based on eqs. (5) and (6), indicated that the size of the cosmic-ray halo should be rather large, $\bar{r} > 5$ kpc (i.e., much larger than the thickness of the galactic disk), for reasonable parameters of the model (Bulanov et al., 1975). In fact, the result of this analysis is a relationship between the diffusion coefficient D and the halo extent $\bar{r}$. This dependence is shown by curve 1 in Figure 2. Thus it was shown that the Galaxy has an extensive cosmic-ray halo for reasonable values of the magnetic field strength.

An important success in the field of radio– and cosmic-ray–halo studies was the discovery in 1977 of pronounced radio halos in the edge-on galaxies NGC 4631 and NGC 891 (Ekers and Sancisi, 1977; Beck et al., 1979). For later observations of radio halos we refer to the review by E. Hummel presented at this Symposium. It is important to notice that the radio observations of edge-on galaxies provide most likely only a lower limit to the size of the cosmic-ray electron halo. Firstly, the sensitivity of the radio telescope is a limiting factor. Secondly, the size of the observed radio halo is not only determined by the electron distribution, but also by the magnetic-field distribution. As the energy density of the magnetic fields decreases towards the periphery of the Galaxy, the cosmic-ray electron halo may be larger than the radio halo.

4. CHEMICAL COMPOSITION OF COSMIC RAYS AND THE HALO

A small part of the nuclei observed in the flux of cosmic rays is not ejected by sources, but generated in the interstellar medium through collisions of cosmic rays with the interstellar gas. These are so-called secondary nuclei (primary nuclei are particles ejected by the sources). By measuring the flux of stable secondary nuclei one can estimate the matter thickness x passed by primary cosmic rays in the Galaxy, given by

$$x = \bar{\mathrm{n}} v t, \tag{8}$$

where $\bar{\mathrm{n}}$ is the average gas density in the disk, v is the velocity of the primary nucleus and t is the time the particles spend in the galactic gaseous disk.

The analysis of the value x alone does not allow to estimate the scale height of the cosmic-ray halo. The reason is that the observed chemical composition of cosmic rays (and x) can be reproduced in very different models of cosmic-ray propagation (see e.g. Berezinsky et al., 1990). In other words, the value of x is not (or is weakly) model dependent for stable nuclei. As an example, we consider the equation for x derived in the framework of the diffusion model (Ginzburg and Ptuskin, 1976)

$$x \simeq \frac{\bar{\mathrm{n}} v h_g \bar{\mathrm{r}}}{D} \qquad (H_g/\bar{\mathrm{r}} \ll 1), \tag{9}$$

where h_g and $\bar{\mathrm{r}}$ are the thickness of the gaseous disk and the cosmic-ray halo, respectively. This equation shows that the necessary value of $x \simeq 7$ gr/cm^2 can be obtained for different values of D and $\bar{\mathrm{r}}$. The only condition to be satisfied is that the relation between D and $\bar{\mathrm{r}}$ must be definite. This condition determines the function $D(\bar{\mathrm{r}})$, which is shown in Figure 2 by curve 2. However, in combination with the analysis of the diffuse radio emission, we *can* get unique model parameters. From Figure 2 we see that the two curves describing the cosmic ray chemical composition and the diffuse radio emission intersect at the point: $\bar{\mathrm{r}} \approx 10$ kpc and $D \approx 10^{29}$ cm^2/s. So, we immediately come to the conclusion that the cosmic-ray halo is very extended.

Using these parameters we can estimate the cosmic-ray lifetime T in the Galaxy

$$T \sim \bar{\mathrm{r}}^2/D \simeq 10^8 \text{ years.} \tag{10}$$

At first glance, this estimate is in contradiction with analyses of the secondary radioactive nuclei flux, which give a much smaller value of $T^* \simeq 10^7$ years (Garcia-Munoz et al., 1977). Consequently, the scale height of the cosmic-ray halo cannot be more than 1 kpc. What is the reason for this discrepancy?

The value of T^* is not measured in experiments. It is calculated in the framework of a model of cosmic-ray propagation from measurements of the fraction of surviving radioactive nuclei. The indicated value of $T^* \simeq 10^7$ years has been got from the leaky-box model, which assumes a uniform cosmic-ray distribution everywhere in the Galaxy. In this case the cosmic-ray lifetime in the Galaxy T^* is given by

$$T^* \simeq (1-f)\tau/f \qquad (\tau \ll T^*), \tag{11}$$

where τ is the lifetime of the nucleus with respect to radioactive decay, and f is the surviving fraction of radioactive isotopes.

Let us take as an example the radioactive isotope ^{10}Be measured in the cosmic-ray flux. Its radioactive lifetime $\tau \simeq 2.2 \times 10^6$ years and the fraction f is about 0.15 (Garcia-Munoz et al., 1977). The estimate of T^* from eq. (11) gives the value $T^* \approx 10^7$ years. However, in the case of diffuse propagation in the Galaxy the radioactive nuclei travel during their lifetime a distance of the order $\sqrt{D\tau}$ which is much smaller than the halo scale height $\bar{\mathrm{r}}$ if $\tau \ll T$. So, the distribution of radioactive nuclei is essentially nonuniform in the Galaxy and the leaky-box model cannot be used to estimate the cosmic-ray lifetime. In the case of this nonuniform distribution of radioactive nuclei, we do not calculate from eq. (11) the true lifetime of stable cosmic rays $T \simeq \bar{\mathrm{r}}^2/D$, but a combination of T and τ (Prischchep and Ptuskin, 1975)

$$T^* \approx \sqrt{\tau T}. \tag{12}$$

So, we cannot exclude that really $T^* < T$. The measurements of radioactive nuclei are, therefore, not in contradiction with the extensive halo for the stable nuclei.

5. ULTRA HIGH ENERGY COSMIC RAYS

Let us see now whether the extensive galactic halo is of essential importance for the ultra high energy cosmic rays. The propagation of ultra high energy cosmic rays in the Galaxy was investigated in a paper by Syrovatskii, (1971). It was shown that galactic sources can provide the observed cosmic-ray flux up to energies $E \leq 10^{17}$ eV, if the confinement region is restricted to the galactic disk. Cosmic rays with higher energies are produced by extragalactic sources. However, this analysis did not include the influence of the cosmic-ray halo on cosmic-ray propagation.

The confinement of ultra high energy cosmic rays ($E = 10^{17} - 10^{19}$ eV) by an extended cosmic-ray halo was investigated by Berezinsky et al. (1979). It was shown that even a relatively small flattened halo with a half thickness $\bar{\mathrm{r}} \simeq 3$ kpc retains the particles with energies up to 10^{19} eV for a rather long time if there is a sufficiently strong regular magnetic field component ($\sim 1\mu$G) in the halo. The explanation of this fact is very simple. If the Larmor radius of a particle is smaller than the scale height of the halo, this particle can be returned from the halo to the disk under the influence of large-scale magnetic fields. Figure 3 shows the residence time of cosmic rays in the Galaxy, with (+) and without (o) a cosmic-ray halo. One can see that the residence time of particles with energies $E = 10^{17} - 10^{19}$ eV is significantly larger for the model with a halo. For energies $E > 10^{19}$ eV, the residence time is the same for both cases, i.e. the large-scale magnetic field in the halo does not return the particles with these energies to the disk.

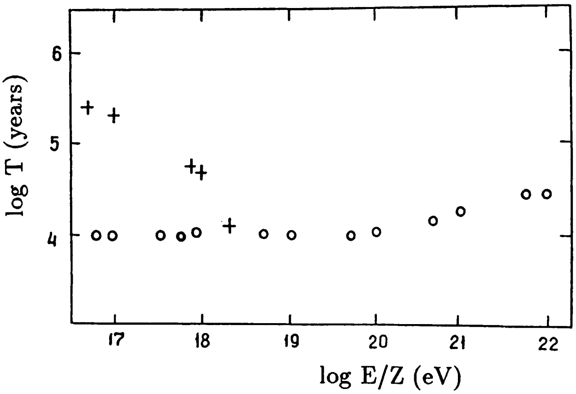

Figure 3. The residence time of ultra high energy cosmic rays in the Galaxy, if a halo exists (+) and if a halo is absent (o).

Due to the larger residence time in case a halo is present, galactic sources can provide the observed cosmic-ray flux at energies $E = 10^{17} - 10^{19}$ eV, which is impossible if a halo is absent.

In the case a halo is present, it is also possible to explain the observed values of anisotropy ($\sim 10^{-4}$) and the intensity of cosmic rays at these energies. The metagalactic models meet serious difficulties in explaining these data, because they give a value for the cosmic-ray anisotropy of about 10^{-5}.

We notice here that the crucial point of this model is the presence of the strong regular magnetic field in the halo. Recently, such regular magnetic fields were discovered in the halo of the galaxy NGC 4631 (Hummel et al., 1988).

6. THE COSMIC-RAY GRADIENT IN THE GALAXY

Gamma-ray astronomy provides methods to address the problem of cosmic-ray propagation in the Galaxy. The point is that the gamma-ray emission from the galactic disk at energies $E > 300$ MeV is mainly due to collisions of cosmic-ray protons and nuclei with the ambient gas (Stephens and Badhwar, 1981)

$$I_\gamma \propto n_H I_{cr} L, \tag{13}$$

where n_H is the average density of the gas along the line of sight, I_{cr} is the intensity of cosmic rays, and L is the length of the disk filled with gas and cosmic rays. It can be seen that gamma-ray astronomy is as important in investigating the proton-nuclear component of cosmic rays as radio astronomy is for understanding the electron component (compare eqs. (6) and (13)), because it provides estimates of the density distribution of this proton-nuclear component in various regions of the disk.

The sources of cosmic rays (supernovae, pulsars and other active stars) are mainly concentrated close to the central region of the disk. Therefore, we can

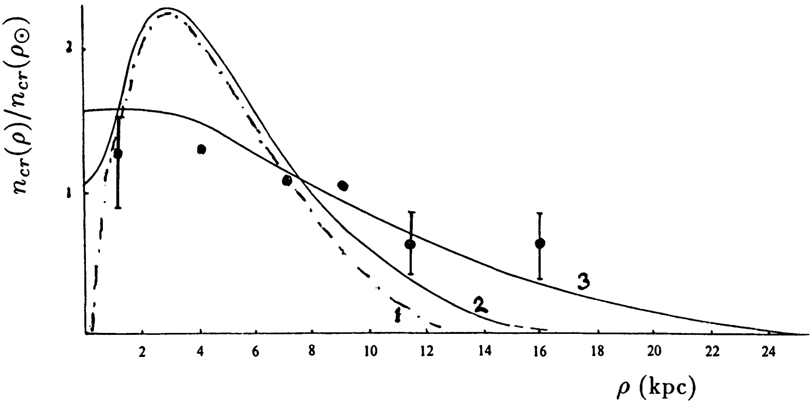

Figure 4. Distribution of the density of cosmic rays in the galactic disk, normalized to the density in the solar neighbourhood, $n_{cr}(\rho_\odot)$. The points indicate the cosmic-ray distribution extracted from the COS-B data (Bloemen, 1989).

1. density distribution of supernovae in the galactic disk.
2. cosmic-ray density distribution for a halo extent $\bar{r}$ = 600 pc.
3. cosmic-ray density distribution for a halo extent $\bar{r}$ = 15 kpc.

expect that the cosmic-ray density also decreases towards the periphery of the Galaxy. However, analyses of disk gamma-ray emission have shown that the gradient of cosmic rays is very small (see e.g. the review by Bloemen, 1989). The gradient of the cosmic-ray density is much less than the gradient of the density of the potential sources (see Figure 4). This fact imposes a strong constraint on models of cosmic-ray propagation in the Galaxy. A similar conclusion was presented by Jones and Stecker (1975). They used a somewhat steeper cosmic-ray gradient, obtained from the SAS-2 gamma-ray data, and derived a halo scale height of about 3 kpc.

In Figure 4, the calculations of the cosmic-ray distribution in the disk (see reviews by Bloemen, 1989; Dogiel and Ginzburg, 1989) are shown for two scales of the cosmic-ray halo: 600 pc (curve 2) and 15 kpc (curve 3). One can see that if the halo is small, the cosmic-ray density distribution becomes similar to the distribution of the sources. This is due to the fact that in the case of a small halo there is little mixing of cosmic rays within the Galaxy. Only in the case of a large halo the results of calculations agree with the distribution of cosmic rays in the disk obtained from the gamma-ray data. From this the conclusion follows that the experimental data point to an effective mixing of cosmic rays in the Galaxy, which is only possible if the Galaxy has an extensive halo. This situation can be understood in the framework of the static halo model. A "very strong" wind suppresses cosmic-ray mixture and the cosmic-ray distribution will in this case be similar to the source distribution, as in the case of a small static halo.

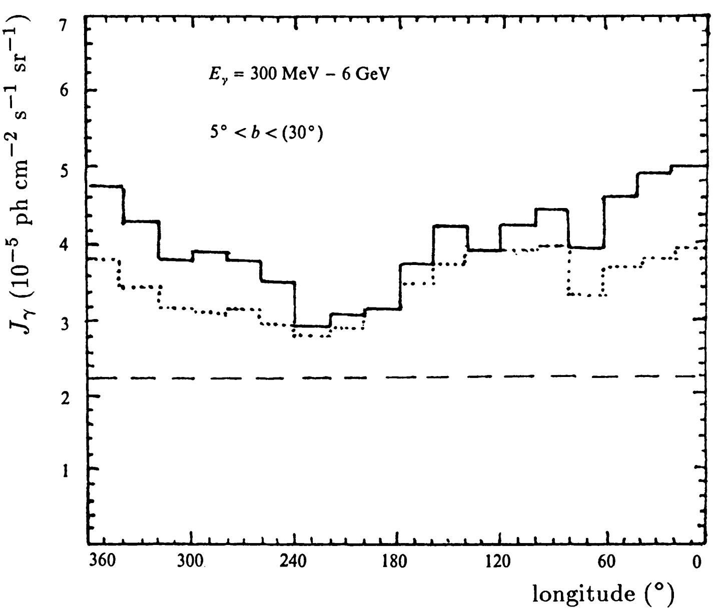

Figure 5. Longitude distribution of the gamma-ray intensity away from the galactic plane. The solid curve is the observed radiation and the dotted curve is the estimated contribution of the gaseous disk.

Another way to investigate this problem was suggested by Melisse and Bloemen (1990). They tried to distinguish between two models of cosmic-ray distribution: the "coupling model" and the "gradient model". In the first model, cosmic rays occupy only the thin gaseous disk and their density is proportional to the gas density. In the "gradient model", cosmic rays have a smoother distribution than the gas distribution and the volume filled by cosmic rays is much larger than the gaseous disk. Their analysis showed that the "gradient model" fits the distribution of the diffuse gamma-ray emission in the disk much better than the "coupling model". This supports the reality of the extended cosmic-ray halo.

7. THE GAMMA-RAY HALO

A noticable flux of radio emission from the halo means that the halo is filled with high-energy electrons (see Section 2). These electrons are also able to produce a gamma-ray flux from the halo through their inverse-Compton scattering on low-energy photons (relic, IR, optical, UV). Let us see if the gamma-ray flux from the halo can be observed and if there are any indications for the existence of this gamma-ray halo.

The estimates by Dogiel and Uryson (1988) show that the halo can account for a substantial part of the observed high-latitude gamma-ray intensity. The estimated gamma-ray flux of the halo is about 3×10^{38} erg/s at energies $E_\gamma > 100$ MeV, which is about 30% of the total gamma-ray flux of the Galaxy.

TABLE 1. Estimates of the extent of the cosmic-ray halo.

Observations	evidence for a halo?	extent
1. Diffuse galactic radio emission	yes	> 5 kpc
2. Edge-on galaxies	yes (for some of them)	$1 - 5$ kpc
3. Chemical composition	model dependent (yes, in combination with radio data)	—
4. Ultra high energy cosmic-ray anisotropy	seems to be yes	$\gtrsim 3$ kpc
5. Cosmic-ray gradient		
a. SAS-2 data	yes	~ 3 kpc
b. COS-B data	yes	~ 15 kpc
6. High-latitude gamma-ray excess		
a. p-p collision origin	yes	$\gtrsim 1$ kpc
b. Inverse-Compton origin	yes	~ 10 kpc

A substantial gamma-ray flux from the halo should show up as an anisotropic gamma-ray component, which is not correlated with the gas column density, i.e. which is not generated in the gaseous disk. An anisotropic excess of gamma-ray emission of this kind was indeed discovered in analyses of the diffuse gamma-ray emission (Bhat et al., 1985; Lebrun and Paul, 1985; Bloemen, 1989). The longitudinal distribution of this excess for the latitude region $5° - 30°$ at energies 300 MeV – 5 GeV is shown in Figure 5, taken from the review by Bloemen (1989). The inverse-Compton scattering of relativistic electrons in a large halo can easily provide the required flux of the gamma-ray excess (see the reviews by Bloemen, 1989, and Dogiel and Ginzburg, 1989). However, this excess could also be due to collisions of cosmic-ray nuclei with the diffuse warm ionized gas with a density of about 0.03 cm^{-3} and a scale height ~ 1 kpc (see Bloemen et al., 1988). Anyway, in both cases the observed gamma-ray excess is generated by the cosmic-ray halo.

8. CONCLUSIONS

Theoretical treatments of the stability of the galactic disk show that it should be surrounded by a region filled with cosmic rays and magnetic fields (i.e., the cosmic halo). The cosmic-ray scattering on magnetic field inhomogeneties increases the life time of cosmic rays in the Galaxy. We define the cosmic-ray halo as a region in which the scattering efficiency is high. The halo extent is different for different components of cosmic rays, but for stable cosmic ray nuclei it is more than 10 kpc. From analyses of observational data, we conclude that the halo existence is doubtless (see Table 1).

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