COSMIC-RAY EVIDENCE FOR A HALO[1]

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1. INTRODUCTION

Cosmic rays were discovered in 1912, but it was only about forty years later that they were found to play an important role in astronomy. Firstly, cosmic rays (including the electron component) are an important source of astronomical information, namely the cosmic synchrotron radiation. Secondly, cosmic rays are essential as energetic and dynamical factors in the galaxy and also as a source of heating and transformation of the interstellar gas composition. Suffice it to remember, for example, that near the solar system the cosmic ray energy density is about the same as the thermal energy of the interstellar gas, and the cosmic ray pressure is likewise about the same as the interstellar gas pressure. Thus, there is every reason to believe that galaxies do not consist of stars and gas only, but of cosmic rays as well.

This conclusion is, of course, well known at present but it is emphasized here because the role of cosmic ray astrophysics in galactic astronomy is still rather small except for the case of the synchrotron radiation theory. It seems to me that to a considerable extent this is explained by the difficulties faced by cosmic ray studies and as a consequence by a comparatively slow progress in this field. As a result, a number of basic questions remained vague for a long time. Seeing that there are disputes in the literature even of a galactic vs. metagalactic origin of cosmic rays and whether galaxies have a radio or a cosmic ray halo, an astronomer is naturally apt to be particularly careful with the cosmic ray data.

Meanwhile, the picture has been significantly clarified (at least in my opinion) concerning the two above mentioned questions. These two problems, especially the halo problem, will be discussed here briefly.

2. COSMIC RAY ORIGIN MODELS

The situation with the cosmic ray origin problem as a whole is presented in Refs. 1-3. In the metagalactic models (e.g. Ref. 4) the cosmic

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rays get into the Galaxy from outside, while in the galactic models the cosmic rays are generated within the Galaxy. The galactic and metagalactic models are so different that without choosing one it is impossible to establish the cosmic ray behavior in the Galaxy. In the case of the cosmic ray electron component, a galactic origin may be considered proved, since Compton and synchrotron losses on the 2.7 K blackbody radiation do not allow electrons of energy $\gtrsim 10^{10}$ - 10^{11} eV formed in other galaxies to reach the Earth or even the Galaxy. However, as far as the proton-nucleon component is concerned, the arguments in the past were for the most part indirect, involving energy considerations, analysis of the charged particle motion, etc. But now with the present data on the intensity of gamma-rays of energies >50-100 MeV in the Galaxy anticenter direction, one can put forward quite direct objections to metagalactic models[1,3,5-8]. (Except perhaps for superhigh energy cosmic rays with energies $\gtrsim 10^{17}$ eV). Meanwhile, no evidence has appeared in favor of these metagalactic models, and so now practically everybody has evidently rejected them and so there is no need to discuss this question further.

3. COSMIC RAY DATA AND THE HALO

In galactic models it is supernovae (including pulsars) that are likely to serve as cosmic ray sources. Even if other active stars or if possible explosions of the galactic nucleus play some role, the sources are in all cases concentrated near the galactic plane, say, within the gas disk with a half-thickness $\sim$100-150 pc. Now, cosmic rays are confined only by the magnetic field frozen in the interstellar gas. The gas is concentrated near the galactic plane due to gravity. However, investigations of the controlled thermonuclear synthesis problem show how difficult it is to keep charged particles even in special laboratory magnetic traps. In cosmic conditions, and in weak fields it is all the more difficult. Thus, the data on gas clouds far from the galactic plane (at $z \gtrsim 1$ Kpc) and radioastronomical observations also leave no doubt that cosmic rays in the Galaxy do not remain in the gas disk region but occupy some region with a characteristic halfthickness >>100-150 pc. This is the region to be called a "cosmic ray halo".

What conclusions concerning the cosmic ray halo can be made on the basis of the data on cosmic rays near the Earth? The essence of the matter is such that for its analysis one should use various data (often quite indirect) which only in total makes it possible to arrive at more or less definite conclusions. Since we cannot here go into details (see Refs. 1, 2, 3, 5-7) we shall first of all formulate the results. Firstly, there are no indications *against* the assumption that the Galaxy has a large (quasi-spherical) cosmic ray halo with a characteristic scale height $\sim$10 Kpc, and with cosmic rays at an energy density near that at Earth. Secondly, even beside the radio data there exists some information and arguments in favor of the model with a large halo, although it cannot be considered proved.

Not to touch upon radiodata and the already mentioned cosmic-ray confinement arguments and the presence of gas clouds at large z, one may involve the results of the investigations of cosmic ray anisotropy and elemental and isotopic composition. Cosmic ray isotropy is so high that their anisotropy has even not yet been reliably established. At energies below 10^{12} eV the anisotropy coefficient is $\lesssim 10^{-3} - 10^{-4}$. High isotropy is quite natural in a model with a large halo where the cosmic ray concentration gradients are small. It is obvious, however, that such an argument taken separately is not weighty enough.

The data on the elemental composition of stable nuclei in cosmic rays leads to the conclusion that they pass through a thickness $x \sim 5$ g cm^{-2} in the interstellar medium (evaluated for pure hydrogen). Now, if the cosmic ray "trapping" region is a gas disk, then the density $n \sim 1$ atom cm^{-3}, and the time required to traverse the 5 g cm^{-2} is about 3×10^6 years. If the particles are trapped in a large halo but their passing through the disk is taken into account, then, approximately $n \sim 10^{-2}$ and the lifetime is 3×10^8 years. So, knowing the thickness x, we cannot yet find the cosmic ray lifetime, and so the halo dimension remains unknown. However, the situation is different when one considers secondary radioactive nuclei (e.g., ^{10}Be which decays into $^{10}B + e^-$ with a mean lifetime 2.2×10^6 years). Knowing x for stable nuclei, and the relative number of ^{10}Be in the cosmic rays, one can already find the cosmic ray lifetime. According to the data available[9] for ^{10}Be the lifetime is 1.7×10^7 years, whence $n = 0.2$ atoms cm^{-3} for the cosmic ray trapping region. This is already proof (though not rigorous) of the fact that cosmic rays leave the gas disk.

At the same time these data by no means contradict the model with a large halo. This is because if the radioactive nuclei lifetime is not large enough, these nuclei have no time to fill up the halo. In other words, for a large halo the radioactive nuclei, the same as relativistic electrons, fill only part of the halo; they pass only to the distance z corresponding to their lifetime. Summarizing, it may be said that at present the direct data on cosmic rays near the Earth only do not contradict the model of a large halo, while they do show that cosmic rays go rather far beyond the gas disk.

4. RADIOASTRONOMICAL EVIDENCE FOR THE HALO

The most reliable of all now available methods of halo study is a radioastronomical one, although it enables one to judge only the halo for the cosmic ray electron component or, as it is often referred to, a radiohalo. The radiohalo is due to synchrotron and Compton losses of the electrons in the magnetic field of the halo region. Unfortunately, the question of a radiohalo of the Galaxy has appeared to be not only difficult to answer, but is has also aroused objections and unpleasant arguments. To my mind several reasons may exist for this situation.

Firstly, being inside a radiating system it is difficult to establish its dimensions and other parameters. Indeed, solutions of the integral equations yielding the radioemission intensity are known to be rather complicated and unstable. And, the presence of discrete sources and various background inhomogeneities complicate the whole picture. Thus, a problem which is simple at first sight is in fact rather complicated, which has aroused errors and misunderstandings and as a result irritation.

Secondly, the radiohalo is often understood as only a spherical or in any case a quasispherical system, and so radiohalo is opposed to radiodisk. However, the difference between halos with scale heights of 1 Kpc vs. 10 Kpc depends to a great extent on the specification of the meaning of the scale height parameter, and so this whole question is of secondary importance. Even so, radiohalo and radiodisk remain opposed in the literature.

A third reason may lie with the desire to solve the radiohalo problem using the minimum of model and theoretical considerations. Such an approach is often, but not always, justified. One cannot make great progress in many radio-astronomical problems when disregarding the synchrotron theory of cosmic radio-emission. The radiohalo problem is not an exception.

I should like to emphasize that I have never (after the work by Pikelner[10]) doubted the existence of a cosmic ray and radio halo, and I believe in it all the more now. The preceding review of reasons for doubting the radiohalo involve problems I consider to be hypothetical. However, I wanted to present them here because I cannot attend the Symposium and discuss this question with colleagues. At the same time I would like to know their opinion.

5. HALOS IN OTHER GALAXIES

Now, the above mentioned difficulties in the study of the galactic radiohalo must to some extent be absent in the observations of other normal edge-on galaxies. What is the observational situation on this question? In NGC4631 such a halo does exist and it is rather bright even at very short wavelengths[11,12]. A radiohalo has also been discovered[13] for edge-on galaxy NGC 891. In fact, I do not know a single case, when a normal spiral edge-on galaxy with a rather high radio-emissivity in the galactic plane had no radiohalo of the type discovered for the above mentioned galaxies.

Summarizing we may state that our Galaxy and similiar ones have a radiohalo, but perhaps this halo is somewhat flattened and less powerful than it was sometimes supposed before. The present report may appear to achieve its goal if it will stop useless arguments concerning the very existence of a radiohalo.

Future work concerning the halo in our own Galaxy should use a broad observational approach. Namely, one should use not only the radio data but also the data on cosmic rays near Earth (elemental and isotopic composition, spectra of protons, nuclei, antiprotons, electrons and positrons, anisotropy) as well as gamma-astronomical information. I am sure that in doing this we should deduce galactic models with a large, or, in any case, a considerable cosmic ray halo. Comparison of all the data will make it possible to specify these models and select the best one.

NOTES

1. This version of V.L. Ginzburg's paper was condensed by G.M. Mason, Dept. of Physics, University of Maryland, College Park, MD USA. The full text has been submitted to Astrophysics and Space Science.

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DISCUSSION

Felten: It appears that Prof. Ginzburg still feels that a cosmic-ray halo with a scale height of 10 kpc is compatible with the data, whereas Stecker says that it must be more like 3 kpc. Can a halo as thick as 10 kpc preserve the correlation between cosmic-ray source positions and cosmic-ray densities which Stecker claims is present in the gamma-ray data? Can a halo as thin as 3 kpc account for the high isotropy of the cosmic rays?

Stecker: Prof. Ginzburg's arguments concerning the cosmic-ray evidence for a halo are, I believe, basically correct. I do, however, believe that the γ-ray evidence is not as ambiguous concerning the size of the halo as the cosmic-ray evidence. The γ-ray evidence favors a flattened halo. It appears to me from the tone of Prof. Ginzburg's remarks that he would not strongly oppose this new result. He is arguing more for the existence of a halo on the basis of the cosmic-ray data. I would have liked to hear his response to your question. Because the gyroradius of cosmic rays in the galactic magnetic field is much less than 1 kpc at 1-10 GeV energies, either halo type would be compatible with the isotropy data.

Cesarsky: It is true that the galactic gamma-ray observations discussed during this Symposium rule out the possibility that cosmic rays in the energy range $\sim$ 1 GeV--i.e., the bulk of the observed cosmic rays--can be extragalactic. But the problem is still alive for the higher energy cosmic rays, especially for $E \gtrsim 10^{17}$ eV. The low value of the cosmic-ray anistropy ($\sim 10^{-4}$) mentioned in the paper was measured at energies of a few hundred GeV; it is believed that, at such energies, cosmic ray trajectories suffer considerable deflections while transiting in the solar cavity. Thus, such measurements are, at best, very difficult to interpret, and, at worst, not relevant to the question of cosmic ray isotropy in the galactic disk.

I want to remark that the discussion of a halo from the point of view of γ-ray data presented by Dr. Stecker, as well as that made on the basis of the observed composition of cosmic rays as elluded to by Ginzburg, only refer to a diffusive halo. This type of argument cannot exclude the presence of a halo made up of particles that are leaving the Galaxy, which would still emit radio-synchrotron radiation. The argument presented by Dr. Fichtel excludes the presence of a strong spherical halo of 100 MeV gamma rays. Such γ-rays had been predicted as arising from inverse Compton interaction of cosmic ray electrons and the 3° black body radiation. But we note that such electrons must have an energy $\gtrsim$ 50 GeV; most cosmic ray observers agree now that the electron spectrum at the Sun is very steep beyond such energies. The steepness is attributed to energy losses of the electrons, and so I suspect that any moderately diffusive model would predict stronger lines, and thus even lower fluxes of high energy electrons in the halo--if there is a halo.

Wielebinski: The halo which has aroused so much theoretical discussion is an intense spheroidal object. When a well-calibrated all-sky survey is taken, the "halo" is what is left over after all the other components have been subtracted. There are, of course, several arbitrary assumptions involved in establishing what is local and what is large-scale. Southern radio continuum surveys are particularly vulnerable because there are relatively few foreground features present. The 408-MHz survey of Haslam should allow a good determination of the halo component. If one accepts the results from edge-on galaxies which indicate a weak ellipsoidal halo with increasing spectral index away from the plane, then a halo of this type should be found around the Milky Way.