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On the Nature of the Galactic Halo

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1.

IN 1952 it was shown by one of us[1] that the sources of galactic nonthermal radio emission form a nearly spherical system concentrating toward the plane and the center of the galaxy. It was pointed out independently by the other author[2] that the field between the clouds must be sufficiently strong to retain the cosmic rays in the galaxy. The density of the kinetic energy of the gas between the clouds could be taken as equal to that of the magnetic energy. Thus the velocity dispersion of the rarefied gas in the space between the clouds should be large and form a spherical, not a flat, subsystem. The spherical distribution of the radio emission supports this suggestion. The wide H and K absorption lines appearing in the spectra of early supergiants are also an argument in favor of the reality of fast movements of the rarefied gas. However, L. Spitzer[3] points out that at least a part of these lines belong to the stars. Spectrograms taken by G. Münch show that some of the wide lines consist of a few faint narrow lines. These phenomena may be explained by the density fluctuations of rarefied gas ($k_\nu \propto n^2$), but some other interpretations are also possible. This phenomenon supports the hypothesis that the more rarefied gas possesses a higher velocity dispersion. The existence of wide H and K lines is not the principal argument of this theory. It will be shown below that the gas of the halo is too rarefied to give observable lines.

Spitzer also pointed out that the existence of supersonic motions must lead to rapid energy dissipation. Consequently he considered the galactic halo to be real, and its large size to be maintained by its high kinetic temperature instead of its fast motions. In this case the temperature of the gas in the space between clouds should be about one million degrees, and the concentration derived from the equilibrium condition between the clouds and in the interstellar space must be 5×10^{-4} cm^{-3}.

2.

The only observational data concerned with the halo are supplied by the nonthermal radio emission of the galaxy. J. Baldwin[4] believes that there are two subsystems which could give similar spectra—the spherical halo and the "Oort-Westerhout distribution." This suggestion seems artificial to us and is a consequence of the introduction of some simplified procedures in the treatment of the observational data. Direct observations by B. Mills by means of a "cross" show a gradual increase of brightness towards the equator and a narrow maximum corresponding to the flat subsystem. The radio galaxies NGC 5128, 4486, and 1316 also show bright nuclei and a gradual decrease of brightness in an outward direction. It may be found from an analysis of different radio data and their comparison, that the density of emission near the galactic plane beyond the flat subsystem ($z\approx1$ kpc above the sun) is about 5–10 times larger than that far from the galactic plane ($z\approx10$ kpc).

Let the differential energy-spectrum of relativistic electrons be $dN(E)=KE^{-\gamma}dE$. The emission ϵ_ν per unit volume is then proportional to $KH^{(\gamma+1)/2}\nu^{-(\gamma-1)/2}$ where H is the magnetic field intensity. The average value of γ is found to be 2.6; thus $\epsilon_\nu \propto KH^{1.8}$. The slow decrease of ϵ_ν upwards is the consequence of a slow decrease of K and H. As the electron density and H decrease we can assume K to be proportional to H. The error involved in this assumption is insignificant. Thus $\epsilon_\nu \propto H^{2.8} \propto K^{2.8}$. Introducing the ratio of the value found for ϵ_ν above at $Z\approx1$ and 10 kpc, we obtain the value of H (and consequently K) in the two corresponding regions to be different by a factor of about 2. As the motions of protons and other cosmic-ray particles are similar to that of electrons, their energy density in the upper layer is also about twice smaller than that near the galactic plane and is approximately equal to 0.5 ev/cm^3. The pressure of cosmic rays constitutes a third of its energy density. It is known that cosmic-ray energy density in the solar vicinity is about the same as magnetic energy density ($H\approx10^{-5}$). From this condition we can find, that approximate value of the field strength is about $H_{10}\approx3.10^{-6}$ and $H_1\approx6.10^{-6}$. The possible error involved here is not very large. If the emission of the flat subsystem were also of a nonthermal character, as is suggested by B. Mills, it might be explained by having a field in the spiral arms that is a little stronger than outside these arms.

3.

The magnetic and cosmic-ray pressure at $Z\approx10$ kpc must be balanced by the weight of the gas above this level.

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[1] I. S. Shklovsky, U.S.S.R. Astron. J. **29**, 418 (1952).

[2] S. B. Pickelner, Publ. Crimean Astrophs. Obs. **10**, 74 (1953); Doklady Akad. Nauk. S.S.S.R. **88**, 229 (1953).

[3] L. Spitzer, Astrophys. J. **124**, 20 (1956).

[4] J. Baldwin, Monthly Notices Roy. Astron. Soc. **115**, 684, 691 (1955).

Thus*

$$\int_{10}^{\infty} g\rho dz = \frac{H_{10}^2}{8\pi} + p_{Kr} + \tfrac{1}{2}\rho v_z^2 + p_g \approx 3\frac{H_{10}^2}{8\pi}.$$

The scale height may be taken as 5 kpc. We deduce than n_{10} about 0.6×10^{-2} cm^{-3}, which is ten times larger than Spitzer's value. Spitzer's halo cannot be retained in our galaxy. If the density is large, the temperature cannot be very high, otherwise the clouds would not be in equilibrium. High temperature is not necessary now, since the halo may be supported by magnetic and cosmic-ray pressures. The magnetic field can hardly be regular, since the poloidal field does not keep the cosmic rays, while the toroidal field prevents the cosmic rays from spreading in the galaxy and reveals some other difficulties (large value of the magnetic flux and so on). If the field is not regular it cannot be a static one. The magnetic forces will lead to a motion of the matter; and dynamic equilibrium must be established, when the densities of the magnetic and the kinetic energies are about the same. In this case the mean velocity of macroscopic motions is about 100 km/sec. The gravitational equilibrium for the layer between $Z=1$ kpc and 10 kpc gives an average value n about 10^{-2} cm^{-3}.

4.

The principal objection against high velocity mass motion is the strong energy dissipation in shock waves. However the presence of the magnetic field and the cosmic rays increases the sound velocity. If the magnetic and kinetic energies are the same, the sound velocity in the direction normal to H is equal to, or greater than, the gas velocity. The shock wave is weak in this case and the dissipation is not large. A solution for the weak perpendicular magnetohydrodynamic shock waves has been obtained. According to F. Hoffmann and E. Teller[5] the increase of entropy in such a wave is

$$\Delta S = -\frac{(\Delta x)^3}{12T_1}\left(\frac{\partial^2 p^*}{dx^2}\right),$$

where

$$x=\rho^{-1} \quad p^* = p + (H^2/8\pi\rho).$$

If $p_1 \ll (1/8\pi)H^2$, the equation may be reduced to the form

$$\frac{\Delta Q}{2H^2/8\pi\rho} = \frac{1}{4}\left(\frac{\Delta x}{x}\right)^3.$$

The left side is the ratio of the irreversible heating per unit mass to the total amount of kinetic and magnetic energies per unit mass, as the result of a passage of a single wave. The radiative cooling increases the irreversible dissipation. But this effect is not very pronounced, if $T<25\,000°$. Besides, the reversible transformation of kinetic into magnetic energy retards the individual wave, without decreasing the total average amount of the kinetic energy. The relative compression $\Delta x/x_1$ was calculated by means of the general equations for the perpendicular magnetohydrodynamic waves. If the condition $\frac{1}{2}\rho v^2 = H_1^2/8\pi$ is fulfiled, $\Delta x/x_1 = 0.54$. Consequently, only about 4% of the energy is dissipated in a single wave. If the density of the magnetic energy is greater than that of the kinetic (for instance, if the differential rotation extends the magnetic lines) the relative dissipation decreases as H_1^{-4}. A calculation of the dissipation, taking into account the pressure and the energy density of the cosmic rays, has been made. The same value was obtained.

Let the characteristic dimensions of the motions in the halo be $l_1 \sim 100$ pc. The characteristic time t_1 will then be about 10^6 years. The time of dissipation in the chaotic magnetic field is $t_0 \sim 25t_1$, while in the absence of the field, it will be about t_1. The diminution of the dissipation in the magnetic field may be important not only for the problem of the interstellar gas, but also for that of turbulent motion in stellar atmospheres.

To maintain the motions in the halo a powerful source of energy is required. The power of this source must be about

$$t_0^{-1}\int\left(\frac{H^2}{8\pi}+\frac{\rho v^2}{2}\right)d\Omega = 3\times10^{41} \text{ erg/sec}.$$

All known mechanisms—novae and supernovae explosions, the radiation pressure of hot stars, the expansion of HII regions and the "rocket effect"—are insufficient.

The Dutch scientists showed[6] that the neutral hydrogen in the nucleus of the galaxy ($n_0 \approx 0.4$ cm^{-3}) has a radial velocity dispersion of about 50 km/sec. If the magnetic energy is equal to the kinetic energy, and K is proportional to H, then the radio emission of the nucleus must be about 100 times greater than the radio emission of the halo. This is in accordance with observations and may serve as a proof of the correctness of some of the above suggestions. The magnetohydrodynamic waves must be propagating outward from the nucleus of the galaxy. The energy flow $\frac{1}{2}\rho v^3 S$ is about 5×10^{40} erg/sec, perhaps sufficient to compensate dissipation. The magnetic field of the waves in the vicinity of the nucleus is larger than the mean field in the halo. It explains the large extension of the region where the nonthermal radio emission is relatively strong. This region is considerably larger than the 21-cm region. The increase of nonthermal radio emission toward the nucleus, similar to that of the increase of the density of the magnetic and the

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* The coefficient 3 is too large, but we retain it since according to modern data the energy density of cosmic rays exceeds 1 ev/cm^3, because the energy spectrum of the cosmical particles was prolonged toward the region of small energies.

[5] F. Hoffmann and E. Teller, Phys. Rev. **80**, 692 (1950).

[6] Kwee, Muller, and Westerhout, Bull. Astron. Soc. Neth. No. 498 (1954).

kinetic energies, is also an argument in favor of the hypothesis that the nucleus is the principal factor explaining the motions in the halo. The mechanism supporting the motions in the nucleus is unknown yet, but the motions are observed.

5.

The value of ΔQ permits us to compute the increase of gas temperature when a single wave is passing. For average conditions, $\Delta T_i \approx 30\,000°$. It was calculated that a wave ionizes one percent of the hydrogen. After the time interval t_1, the temperature falls to about 10 000°–15 000°. Every subsequent wave will ionize about one percent of gas. After this, the temperature will again fall to $\approx 10\,000°$. This quantity depends very little upon the initial conditions, because at low temperatures the process of cooling is very slow. The stationary degree of ionization may be from 10 to 80%. It is a function of gas density, of t_1, and of other physical conditions. The ionization would be complete if the magnetic field were absent. The determination of the ionization from observations permits us to define more precisely the rate of dissipation.

6.

The theoretical computation is based upon simple models and may be lacking accuracy. It is necessary to confirm the principal results by means of direct observations. Examples must be given to show the existence of the halo and other gaseous systems with a high velocity dispersion, but with low temperature and ionization. The Australian scientists[7] observed 21-cm isophots for the Magellanic Clouds. These isophots cover a region which is much larger than the region of optical emission. The radial velocity dispersion is about 50 km/sec. The computed concentration of the neutral hydrogen on the periphery of the Large Magellanic Cloud (LMC) is about 0.8×10^{-2} cm^{-3}. LMC has traces of spiral structure. It is probable that LMC has a halo similar to our galaxy. The nucleus of our galaxy also contains partly neutral gas with high velocity dispersion. Observations in the 21-cm region in the Coma Cluster[8] are especially interesting. The mass of neutral hydrogen is about $10^{14}M_{\odot}$, which is nearly equal to the total mass of the cluster from the virial theorem. The great mass, the large extension, and some other reasons lead to a supposition that we have here to do with intergalactic gas. The dispersion of the radial velocity of this gas is about 500 km/sec. If the magnetic field would be absent, this intergalactic gas would be completely ionized. The field may decrease the dissipation in the shock wave, if the energy of the field is not less than the kinetic energy. Consequently, the examples given above represent an argument in favor of the equipartition of the magnetic and the kinetic energy.

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[7] Kerr, Hindmann, and Robinson, Australian J. Phys. **7**, 297 (1954).

[8] D. Heeshen, Astrophys. J. **124**, 660 (1956).

DISCUSSION

G. de Vaucouleurs, *Lowell Observatory, Flagstaff, Arizona:* Is it possible to estimate the total projected surface density of the gas in the corona, and is it possible to estimate the emission measure of this gas according to whether it is caused by excitation by the general radiation field of the galactic plane or possibly by collisions? (*Ed. note:* emission measure$\equiv\int n_e^2 dl$; $[n_e]=\text{cm}^{-3}$; $[l]=\text{pc}$.)

S. B. Pickelner, *Crimean Astrophysical Observatory, Simeis, U.S.S.R.:* The total mass of the rarefied gas in our galaxy is not very large. It is about the same as the total mass of the cosmic clouds. The emission measure of this gas is very low as it is proportional to n_e^2, and this gas cannot be observed without the radio data.

G. de Vaucouleurs: *The question was really,* "Have we a chance to observe this corona in other galaxies?" By using interference filters of very narrow band pass, would it be possible to detect the optical emission of the corona in other galaxies by *Hα* photography?

S. B. Pickelner: The emission measure is about $n^2l\approx10^{-4}\times10^4=1$.

G. de Vaucouleurs: I would like to make a remark about the Magellanic Clouds. I do not think it is quite right to say that the distribution of neutral hydrogen in the Magellanic Clouds, and especially in the Large Cloud, is much broader than the distribution of light. What I call the "effective radius," i.e., the radius within which half the total emission lies, is about 3° for both the 21-cm line and for the continuum radiation at 3.5 meters, while the effective radius for the luminosity in red light is about 2.5°, so there is not much difference. The case of the Small Cloud is not typical, because we have the prominence of hydrogen extending towards the Large Cloud as if the hydrogen had been pulled out of the main plane in this cloud. When we make a comparison between the galaxy and other galaxies, such as the Clouds, we should be very careful not to assume that something that happens in our galaxy can be applied directly to other galaxies and vice versa. It is quite obvious, for instance, that the ratio of hydrogen to total mass changes according to the galactic type and that heavy galaxies do not have the same properties as small galaxies.

L. SPITZER, JR., *Princton University Observatory, Princeton, New Jersey:* I would like to comment on the factor of 10 difference between the Pickelner-Shklovsky value and mine for the density of gas in the halo. In their model of the halo I believe that pressure equilibrium was assumed, in the sense that $B^2/8\pi$ plus the gas pressure is balanced by the downward pull of gravity on the outer layers of gas. I would have supposed that there might also be some magnetic field in this outer region which would diminish the gas density needed for pressure equilibrium. In the extreme case of a nearly force-free field, for example, one can imagine that the magnetic field outside the halo would provide nearly all the inward pressure needed.

S. B. PICKELNER: We considered not only very thin levels, but all the levels above 10 kpc. We think the gas continues to 15 kpc (the scale height is about 5 kpc) and consider the equilibrium of this layer. The field above 15–20 kpc is less than at 10 kpc by about a factor of 2, and the magnetic pressure is unimportant. Other galaxies, for instance Andromeda, also show the radio halo up to 10–15 kpc.

L. SPITZER, JR.: Could one not have a magnetic field without any radio emission?

S. B. PICKELNER: Yes, there may be a magnetic field without radio emission if there are no relativistic electrons, but apparently the radio emission extends to 10 kpc.

L. SPITZER, JR.: You may have already answered in your last remark my second question, which concerned your value of 3×10^{-6} gauss for the magnetic field in the halo, at 10 kpc from the galactic plane. How much could this particular field be reduced and the radio observation still explained?

S. B. PICKELNER: The emission is proportional to $KH^{1.8}$. If we decrease H to about 10^{-6}, we have to increase the relative particle density proportional to $H^{1.8}$, about 8 times. The magnetic pressure will be 8 times less than before, and the cosmic-ray pressure will be about 8 times larger. The discrepancy will be 64 times—too large to be possible.

G. FIELD: Why might we not expect to observe the 21-cm hydrogen emission from this galactic corona as Pickelner has outlined it? That is, if we see it in the Large Magellanic Cloud, wouldn't we see it in our own galaxy as well? I made some rough estimates and conclude that we should be able to detect an antenna temperature of about 1° toward the galactic pole with an approximate width of perhaps 100 km per second. I would then like to ask if there is any evidence for this kind of emission from van de Hulst's work.

S. B. PICKELNER: I did not say that we should not observe it, but it is more difficult to see the radio emission when we are inside the system.

G. FIELD: I think that is probably true. If, on the other hand, there were say 10 degrees of such emission, it would be possible to see it. I would like to ask van de Hulst if there is any evidence on this point.

H. C. VAN DE HULST, *Leiden Observatory, Leiden, Netherlands:* Let me repeat the question: Do you really think there should be atomic hydrogen emission in this halo or not?

S. B. PICKELNER: Yes, I think that 21-cm emission must be present in our galaxy, and indeed in our halo, because the ionization is not complete. This ionization is about 50%, plus or minus 30%. It is, therefore, certainly difficult to decide *a priori* whether the radio emission is observable. It is necessary to have measurements with fine amplifiers.

H. C. VAN DE HULST: Figure 1 of my paper shows emission lines of the 21-cm line in arbitrary points at high latitudes with a maximum temperature of the order of 3°K and a dispersion of the order of 40 km per second. I thought that higher velocities would be needed in order to bring the gas so high above the plane.

S. B. PICKELNER: The wings of the line may be more extensive and weak. On the other hand, it is not only the kinetic pressure but the magnetic pressure and cosmic-ray pressure: three agents.

E. SCHATZMAN, *Institut d'Astrophysique, Paris, France:* I have three questions. First, what is the range of energies of the relativistic electrons you are considering there? Next, what is the proportion of relativistic electrons to all ordinary electrons? Finally, do you have a mechanism for the production of the relativistic electrons?

S. B. PICKELNER: The energy of the relativistic electrons is that usual for radio emission—about 10^9 ev, and it is not important in this analysis. We have some energy spectrum of relativistic electrons, $dN(E) = KE^{-\gamma}dE$, with $\gamma\sim2.6$. The total quantity of relativistic electrons is less than 1% of the ordinary electrons. I have not computed this value exactly; it is not necessary for the present purpose. The concentration of the ordinary electrons is between one and five times 10^{-3} cm^{-3}, depending upon the stage of ionization. Finally, we do not know the origin of the relativistic electrons. But the presence of these electrons follows from the radio emission, from the polarization of the Crab Nebula, and from the polarization of M 87 and other observational facts.

E. SCHATZMAN: Possibly the number of relativistic electrons is larger than the number of ordinary electrons.

S. B. PICKELNER: If the number of relativistic electrons were so large, we would observe very powerful radio emission. This can be calculated.

MORRISON: *Cornell University, Ithaca, New York:* What fraction of the energy dissipation of the halo is due to loss of cosmic rays out of the halo?

S. B. PICKELNER: I think that this value is less than the dissipation by shock waves. The dissipation by the cosmic-ray production is the same as the total energy which we can get from the HII expansion zones. But the total energy dissipation of the halo is about 10 times larger.