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INTERGALACTIC MATTER AND THE GALAXY

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ABSTRACT

It is shown that the Local Group of galaxies can be dynamically stable only if it contains an appreciable amount of intergalactic matter. A detailed discussion shows that this matter consists mainly of ionized hydrogen and that stars can contribute only a small fraction to its total mass. The most likely values for the intergalactic temperature and density are found to be 5×10^5 degrees and 1×10^{-4} proton/cm^3, respectively. It is thought that this gas confines the halo. The distortion of the disk of the Galaxy, revealed by 21-cm observations, is analyzed. This effect cannot be regarded as a relic from a primeval distortion, which occurred at the time of formation of the Galaxy; a more promising explanation for it can be given in terms of the flow pattern of the intergalactic gas past the Galaxy and of the resulting pressure distribution on the halo.

I. INTRODUCTION

It is well known that the density of galaxies in our neighborhood is larger than the average. This has led to the theory than our Galaxy is a member of the so-called Local Group, a group similar to the fairly numerous small groups of galaxies found all through extragalactic space. It seems reasonable to assume that most of these groups are systems of negative energy, i.e., that they are held together by gravitational forces. We shall show that this is possible for the Local Group only if intergalactic matter is present. Subsequently, we shall discuss the nature of this intergalactic matter and its effects on our Galaxy. Our discussion is exploratory, and a number of problems, like the detailed structure and the general stability of the galactic halo, are left untouched.

II. DYNAMICS OF THE LOCAL GROUP

About a dozen galaxies are known to belong to the Local Group, and some more are suspected of being members. Most of these galaxies are intrinsically faint. The Andromeda Nebula and our galaxy are by far the largest and most massive systems in the Local Group. Together with their companions, they contribute between 80 and 90 per cent of the total observable mass. Thus, unless a few massive galaxies are hidden by absorption in the galactic plane, M31 and our Galaxy are dynamically the only important members and, in the absence of intergalactic matter, would essentially form a simple

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double galaxy. We shall adopt the following data: The masses of M31 and of the Galaxy with their companions are about 4×10^{11} and 1×10^{11} solar masses; their distance apart is 600 kpc (cf. Schmidt 1956, 1957).

The radial velocity of M31 with respect to the local standard of rest near the sun is -296 km/sec, according to the accurate 21-cm data (van de Hulst *et al.* 1957). With a circular velocity of 216 km/sec near the sun (Schmidt 1958), we find that the centers of M31 and of our Galaxy approach each other with a speed of 125 km/sec. An estimated uncertainty of ± 25 km/sec in the circular velocity near the sun makes this figure uncertain by ± 20 km/sec. The fact that the motion is one of approach is significant. For if the Local Group is a physical unit, the Galaxy and M31 are not likely to have been formed very far from each other, certainly not at a much greater distance than their present separation. This indicates that they must have performed the larger part of at least one orbit around their center of gravity during a time of about 10^{10} years. Consequently, their orbital period must be less than 15 billion years. From this we obtain the total mass of the system as follows. According to Kepler's third law, we have

$$P^2 = \frac{4\pi^2}{GM^*} a^3 \leq 2 \times 10^{35} \text{ sec}^2, \tag{1}$$

where M^* represents the effective mass at the center of gravity. To obtain a minimum estimate for M^*, we assume that the system has no angular momentum. Then conservation of energy gives, for our Galaxy,

$$\frac{GM^*}{2a} = \frac{GM^*}{D} - E_k, \tag{2}$$

where D denotes the present distance of the Galaxy to the center of gravity (480 kpc) and E_t is its present kinetic energy per unit mass. From these equations we obtain

$$M^* \geq 1.8 \times 10^{12} m_\odot , \tag{3}$$

which is six times larger than the reduced mass of M31 and the Galaxy.

The discrepancy seems to be well outside the observational errors. Even without an argument about the period, the difficulty persists. At present the kinetic energy of the system is 12.5×10^{57} ergs, or more, whereas the gravitational energy is only -6×10^{57} ergs. Thus, without additional matter, the system would have positive energy.

These results indicate that there must be at least 1.5×10^{12} solar masses of intergalactic matter distributed in the Local Group well within the present position of the Galaxy. An alternative possibility is that this mass is spread homogeneously all through the Local Group, extending well outside the present position of the Galaxy. In this case the equation of motion of the Galaxy with respect to the center of mass of the Local Group is

$$\ddot{r} + \tfrac{4}{3}\pi G \rho r = 0, \tag{4}$$

where ρ is the density of the intergalactic medium. The period of the orbital motion of the Galaxy now is

$$P = \frac{2\pi}{\sqrt{\tfrac{4}{3}\pi G \rho}}. \tag{5}$$

Assuming, now, that $\frac{1}{2}P$ is smaller than 1.5×10^{10} years (since half an orbit now is equivalent to a complete one in the preceding discussion), we obtain

$$\rho \geq 1.6 \times 10^{-28} \text{ gm cm}^{-3} . \tag{6}$$

III. THE NATURE OF THE INTERGALACTIC MATTER

The intergalactic matter needed for the dynamical stability of the Local Group may consist either of stars or of gas or of both. There is evidence that some intergalactic stars exist in the Local Group.

Recently two star clusters have been found (E. M. Burbidge and Sandage 1958) at distances of over 100 kpc, which are definitely intergalactic. It might also be argued that Zwicky's luminous bridges, some of which certainly consist of stars (Zwicky 1958), indicate the existence of intergalactic stars in general. However, these objects seem to be due to a strong interaction between two or more galaxies. No evidence exists to suggest that such bridges are present in the Local Group.

Oort (1958) has pointed out that at least four RR Lyrae stars are known with velocities in excess of the velocity of escape from the Galaxy. Oort considers these stars to be interlopers from intergalactic space; he suggests that the total mass of intergalactic stars in the Local Group may amount to ten times the mass of the visible galaxies, if these RR Lyrae stars are part of some halo-type stellar population. This estimate, however, is quite uncertain. As Oort points out, an increase by one in the absolute magnitude of these RR Lyrae stars would be sufficient to make them regular galactic stars. A change in this direction is not at all improbable. Moreover, the velocity of escape from the galactic system is not too well known.

Though it is certain that an intergalactic stellar population does exist, we are extremely reluctant to believe that it is the main contributor to the mass of the Local Group. Our reasons are as follows: The smallest galaxies of the Local Group are the dwarf galaxies, which have fairly small masses. Only half a dozen such systems are known. Their contribution to the total mass is insignificant, even if a large number of them still remains undiscovered. Globular clusters also do not contribute significantly. Schmidt (1956) finds 7×10^{-4} globular clusters per kpc^3 brighter than $M_{pg} = -5$ in the polar regions of our Galaxy between 13 and 19 kpc from the galactic center. Even if all of them were intergalactic, which is improbable, their contribution to the total mass of the Local Group would not be very significant. Thus, if the intergalactic medium consists mainly of stars, these stars either must be single stars or must occur in small groups of no more than a few thousand members. It is very difficult to see how such small groups could condense at all from the intergalactic medium, and it is even more difficult to envisage a process which would lead to the formation of a dozen galaxies and a billion very small clusters. Since no objects are known intermediate in size between the larger globular clusters and the smaller dwarf galaxies, we are inclined to consider the latter as the smallest units formed directly from the intergalactic medium; the former are presumably the largest masses able to form in the Galaxy after it had condensed from the intergalactic medium. The intergalactic stars present have probably come from disrupted dwarf galaxies or have been ejected from the larger galaxies.

As remarked above, the argument for intergalactic RR Lyrae stars is extremely uncertain. One could check it by looking for RR Lyrae stars near the galactic poles. About 25 such stars between the seventeenth and twentieth magnitudes are to be expected per square degree if Oort's argument is valid. Even now it seems somewhat difficult to explain why no intergalactic RR Lyrae stars were found in the variable survey in M31 by Baade and Miss Swope (1955), which covered about one-sixth of a square degree to beyond the twenty-second magnitude.

We are thus inclined to consider that gas makes up the main component of the intergalactic medium in the Local Group. If few stars are present, this gas should be almost pure hydrogen, possibly mixed with helium. Direct observational evidence for such gas, if ionized, is hard to obtain. It may, however, have observable effects on our Galaxy, as shown in the following sections.

We shall now make some estimates of the physical conditions in the gas. In the preceding section we obtained the minimum mass of the gas if most of it lies well within the present position of the Galaxy and the minimum density if it stretches farther out. In Figure 1 we have plotted the resulting minimum mean density of the gas as a function of the outer radius of the gas cloud.

The gas may be in equilibrium under its own gravitation, or it may be confined by a hotter, more tenuous general intergalactic medium. The latter possibility seems somewhat unlikely in an expanding universe. But if the gas is self-gravitating, the virial theorem gives us the relation

$$2U+\Omega=0 \,. \tag{7}$$

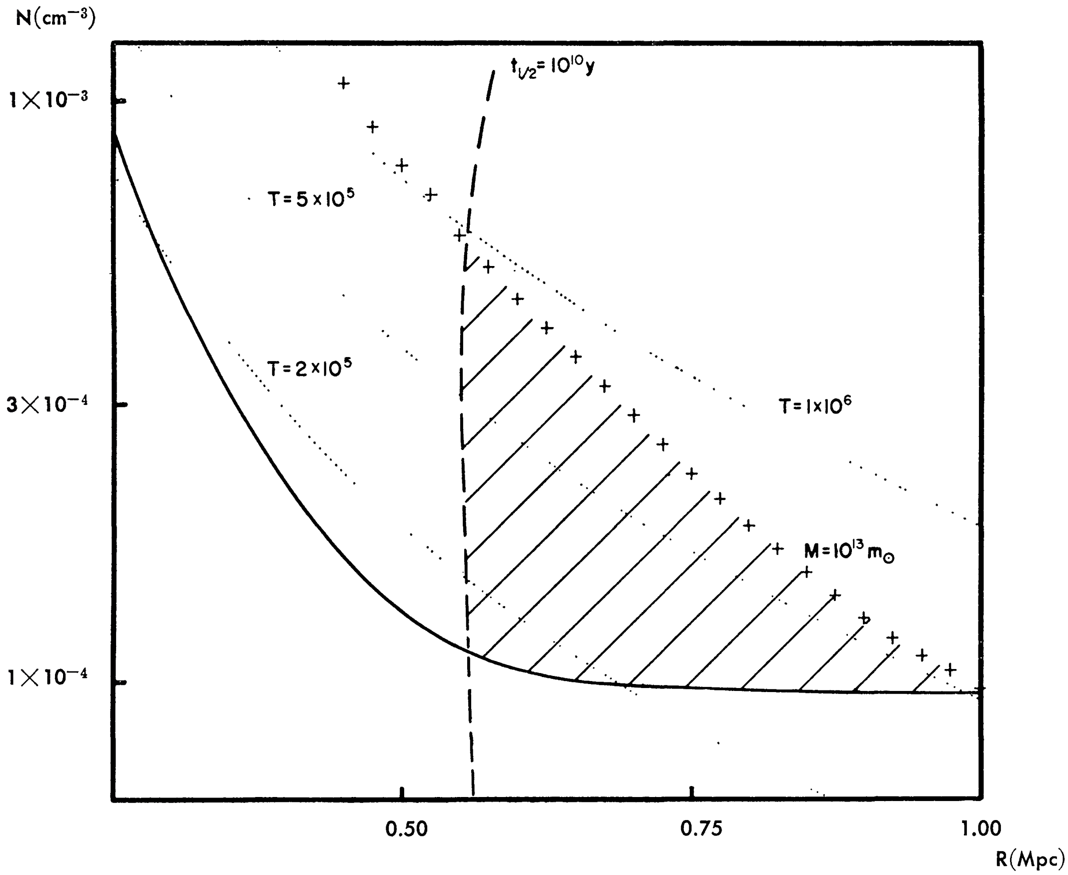

FIG. 1.—Possible physical conditions in the intergalactic gas. Each point in the diagram corresponds to a given value of the mean density of the gas (N cm^{-3}) and of the outer radius of the configuration R. Points below the solid line do not satisfy the dynamical requirements for the Local Group. Configurations to the right of the dashed line and to the left of the crosses have cooling times longer than 10^{10} years and masses less than $10^{13}m_\odot$.

To obtain a rough estimate, we assume uniform density and temperature in the gas. Then equation (7) is equivalent to

$$8\pi R^3 N kT=\frac{3}{5}\frac{GM^2}{R}=\tfrac{16}{15}\pi^2 G\rho^2 R^5 \tag{8}$$

if the gas is fully ionized. Thus the temperature, T, is a function of the gas density (N protons cm^{-3}) and the radius of the configuration, R. And in Figure 1 we can determine the temperature at every point. A few isotherms are indicated by broken lines.

If the cooling time of the gas were short compared to the age of the Local Group, the gas would have contracted and condensed into galaxies. The radiation rate for ionized hydrogen is (Minkowski 1942)

$$\frac{dU}{dt} = -1.45 \times 10^{-27} T^{1/2} \left(1 + \frac{3.85 \times 10^5}{T}\right) N^2 \text{ erg cm}^{-3} \text{ sec}^{-1}. \tag{9}$$

The thermal energy per cubic centimeter is

$$U = 3NkT \,, \tag{10}$$

and a time characteristic for the cooling process is

$$t_{1/2} \simeq \frac{U}{dU/dt} = \frac{9 \times 10^3 T^{1/2}}{N[1 + (3.85 \times 10^5/T)]} \text{ years} \tag{11}$$

and is a function of N and T only. In Figure 1 we have plotted the locus of points for which the cooling time is 10 billion years. It is seen from this curve that it is implausible for the gas mass to have a radius smaller than $\frac{1}{2}$ Mpc. Thus the gas seems to surround the Galaxy. Finally, we have plotted in Figure 1 the locus of the points corresponding to configurations with a mass of $10^{13} m_\odot$. This value would correspond to an M–L ratio of of about 400 for the Local Group; in view of results on larger clusters, it seems somewhat doubtful to us that this ratio can be exceeded. If we accept this upper limit to the mass, we see in Figure 1 that the physical conditions in the gas are fairly well determined. In the following we shall adopt

$$N = 1 \times 10^{-4} \text{ cm}^{-3} \,, \qquad T = 5 \times 10^5 \,. \tag{12}$$

If the intergalactic gas consists of fully ionized hydrogen, the mean free path for the particles in it is given by

$$l = \frac{0.4}{[\ln(x-2)]} \frac{(kT)^2}{Ne^4}, \tag{13}$$

where e is the electronic charge in e.s.u. and $x = 4kT/N^{1/3}e^2$ (this formula is adapted from one given by Chapman 1954). With our values for T and N,

$$l \simeq 2 \times 10^{19} \text{ cm} \simeq 7 \text{ pc} \tag{14}$$

and is small on the galactic scale.

The speed of sound in the gas is

$$a = \left(\frac{\gamma P}{\rho}\right)^{1/2}. \tag{15}$$

With $\gamma = \frac{5}{3}$, $P = 2NRT$, and $\rho = Nm_H$ (m_H is the mass of the hydrogen atom), we obtain

$$a = 120 \text{ km/sec} \,. \tag{16}$$

This value is correct only for wave lengths which are so long that heat conduction is negligible and the motion of the gas is adiabatic. In an ionized gas, thermal energy is transferred mainly by the electrons, which have high random velocities. The thermal conductivity, σ, is of the order of $1(kT/m_e)^{1/2} = 6 \times 10^{27}$ cm²/sec, and so heat conduction may be neglected whenever the wave length of the disturbance satisfies

$$\lambda \gg \frac{\sigma}{a} = 170 \text{ pc}. \tag{17}$$

This condition holds for any intergalactic application.

We have already seen that the gas is a poor radiator of heat and therefore conclude that all its motions may be treated as adiabatic.

In the following two sections we shall consider two ways in which the presence of intergalactic matter may influence the structure of the non-stellar components of our Galaxy.

IV. THE EQUILIBRIUM OF THE GALACTIC HALO

It is now widely believed that our Galaxy and many other spiral nebulae have halos containing cosmic-ray particles and relativistic electrons (Spitzer 1956, Pikel'ner and Shklovsky 1957). The presence of a magnetic field prevents the escape of these high-energy particles. In the case of our Galaxy the halo has a diameter of some 30 kpc, and the field strength, at large distances from the plane of the Galaxy, is of the order of 2×10^{-6} oersted. This value is somewhat lower than the value derived by Pikel'ner and Shklovsky, who made the incorrect assumption that the density of relativistic electrons is proportional to the strength of the magnetic field. It follows from Liouville's theorem and from the fact that the energy of a gyrating particle is a constant of motion that the density tends to be constant along the field lines in a steady state.

There may also be some ionized gas distributed in the halo. Spitzer estimates that its temperature is 5×10^6 degrees and its density 5×10^{-4} particle/cm^3. Pikel'ner and Shklovsky consider these values to be unlikely and propose instead that the gas has a temperature of about 10^4 degrees and a density of 10^{-2} particle per cm^3. They suggest that a kind of hydromagnetic turbulence, with a high Mach number, provides the effective pressure which supports this gas against gravitation. On the other hand, a layer of quiescent gas outside the halo prevents the escape of the halo material, in which a fairly large magnetic pressure is present, into intergalactic space. Pikel'ner (1957) has given reasons for believing that this type of turbulence does not rapidly decay into thermal energy, but his argument applies only to disturbances traveling across the magnetic field. On the other hand, we should expect a much faster rate of decay for a pressure wave traveling along the lines of force.

Even without any dissipation inside the halo, the hydromagnetic waves still carry energy to the boundary of the halo and transfer it there to the quiescent layer of gas with surrounds it. The rate of transfer of energy outward is of the order of $\rho u^3 S$, where ρ is the density, u is a typical turbulent velocity, and S is the surface area. The total energy content in the volume, V, of the halo is of the order of $\rho u^2 V$, and the decay time of the turbulence, then, is about $V/uS \simeq R/u$, or approximately the time of free fall of a particle, i.e., about 50×10^6 years. As Pikel'ner and Shklovsky themselves point out, it is difficult to supply energy at such a high rate. In addition, it seems likely that the quiescent layer of gas outside the halo would become turbulent and would be blown off.

We propose a different geometry for the magnetic field in the halo. Observations of interstellar polarization show that the lines of force more or less follow the spiral arms of the Galaxy. From this, one can conclude that the field near the galactic plane is largely toroidal. But the field in the halo will also have appreciable poloidal components. This is indicated by the fact that the synchrotron electrons seem to be able to travel to the outer regions of the halo. The poloidal component of the field may in part be due to currents in the galactic plane, where a Lorentz force can be balanced. There will also be current systems in the halo and something like surface currents on the boundary of the halo, which shut off the poloidal field from intergalactic space and, in addition, produce the toroidal field. We think that the Lorentz force at the surface is balanced by the inward pressure of the intergalactic gas, whose order of magnitude we shall now estimate.

The pressure P and the density ρ of the intergalactic gas, assumed to be stationary for the moment, can be found from Bernouilli's equation,

$$\frac{\gamma}{\gamma-1}\left[\frac{P}{\rho}-\frac{P_\infty}{\rho_\infty}\right]=\frac{GM}{R}, \tag{18}$$

or

$$5\left[\frac{kT}{m_{\rm H}}-\frac{kT_\infty}{m_{\rm H}}\right]=\frac{GM}{R}, \tag{19}$$

where M is the mass of the Galaxy, R is the radius of the halo, and P_∞, ρ_∞, and T_∞ are the pressure, density, and temperature at infinity. It has been assumed that the relation between pressure and density is the adiabatic one, an assmuption justified in the following section. With $M = 10^{11} m_\odot$, $R = 15$ kpc, and $T_\infty = 5 \times 10^5$, the equation leads to $T - T_\infty \simeq 7 \times 10^5$. Thus $T = 1.2 \times 10^6$ and $T/T_\infty = 2.4$. Since P varies as $T^{5/2}$ and ρ and $T^{3/2}$, we find at the boundary of the halo that $P = 9P_\infty = 1.3 \times 10^{-13}$ dyne cm^{-2} and $N = 3.6\,N_\infty = 3.6 \times 10^{-4}$cm^{-3}. The intensity of the magnetic field confined by the inward pressure is given by $H \doteq (8\pi P)^{1/2} = 1.8 \times 10^{-6}$ oersted. This has the right order of magnitude. The intergalactic pressure thus provides a natural explanation for the confinement of the halo.

A criterion can be found to decide whether this system is stable against a change in the volume of the galactic halo. If the radius of the halo is altered from R to $R + \delta R$, the change in the gas pressure on its boundary is given by

$$\delta P = -\frac{GM}{R^2}\,\rho\,\delta R. \tag{20}$$

Since the magnetic-field strength varies as R^{-2}, the corresponding change in the magnetic pressure, P_m, is

$$\delta P_m = -\frac{4P_m}{R}\,\delta R. \tag{21}$$

The system is stable against this perturbation if

$$\frac{GM\rho}{R^2}<\frac{4P_m}{R}=\frac{4P}{R}, \tag{22}$$

or

$$\frac{GM}{4R}<\frac{P}{\rho}=\frac{2kT}{m_{\rm H}}. \tag{23}$$

Because of equation (19), the inequality is always satisfied. In other words, any galactic halo can adjust its volume so as to balance the inward pressure of the intergalactic medium.

To conclude this section, we shall show that the mean free path in the intergalactic gas is much larger than the distance over which an incident charged particle interacts with the halo field and that all the electrons and protons are reflected specularly.

The depth to which a particle penetrates into the field has the same order of magnitude as the Larmor radius, $r_L \simeq m\bar{v}c/eH$; since the particle pressure on one side balances the magnetic pressure on the other, we have $N_m\bar{v}^2 \simeq H^2/8\pi$. Thus $r_L \simeq (mc^2/8\pi Ne^2)^{1/2}$, and, with $N \simeq 10^{-4}$ cm^{-3}, we find $r_L = 4 \times 10^7$ cm for electrons and 2×10^9 cm for protons, both much smaller than the mean free path, which is several parsecs.

The equation of motion of a particle in the field is

$$\ddot{r}=\frac{e}{mc}\,\dot{r}\times \boldsymbol{H}, \tag{24}$$

from which it follows at once that the particle speed remains constant. If the field has the form

$$\boldsymbol{H}=[H_x(z)\,,\,H_y(z)\,,\,0]\,, \tag{25}$$

then, on vector multiplication of the equation of motion with $\boldsymbol{k} = [0, 0, 1]$, we find

$$\ddot{\boldsymbol{r}} \times \boldsymbol{k} = \frac{e}{mc} (\dot{\boldsymbol{r}} \times \boldsymbol{H}) \times \boldsymbol{k} = \frac{e}{mc} H(z) \dot{z}. \tag{26}$$

On integration, we obtain

$$\dot{\boldsymbol{r}} \times \boldsymbol{k} = \frac{e}{mc} \int H(z)\, dz, \tag{27}$$

so that the x and y components of the particle velocity are functions of z only. It follows that a charged particle has the same tangential velocity components before and after reflection. Since the particle speed remains unchanged, the reflection must be specular.

V. THE DISTORTION OF THE GALACTIC DISK

Recent 21-cm observations have shown that the distribution of hydrogen gas in the galactic disk is not exactly plane but shows systematic deviations from perfect flatness in its outer parts. Between galactocentric longitudes $L = 0°$ and $L = 120°$ and beyond 10 kpc galactocentric distance, the gas lies above the plane; in the opposite position it lies systematically below the plane (Oort, Kerr, and Westerhout 1958). Here we have defined galactocentric longitudes so that the sun is situated at $L = 147.5$. There are two possible explanations: either there is a system of forces, acting from outside on the Galaxy, which produces this distortion, or else, as has occasionally been suggested, the Galaxy was formed distorted and has remained so. We favor the first of these alternative possibilities and shall first show that the second one leads to difficulties.

Let a set of stars and some diffuse matter be distributed in a disk which is in differential rotation and whose shape resembles that of the present distribution of gas. Consider the motion of these particles in the gravitational field due to an ellipsoidal mass distribution in the inner parts of the galactic system. If the gravitational field has spherical symmetry and if none of the orbits is too elliptical, then the shape of the distortion remains unchanged with time. But if the field deviates slightly from spherical symmetry, i.e., if the axial ratio of the mass ellipsoid differs from unity, the distortion is smeared out.

Let us, for simplicity, assume that all orbits are circular. Let the gravitating matter have a mass M and let the principal moments of inertia of its distribution be A, A, and C. We neglect the self-gravitation of our set of particles. Let us choose cylindrical coordinates, with the axis of the Galaxy in the z-direction. The gravitational potential is

$$V = \frac{GM}{(\varpi^2 + z^2)^{1/2}} + \frac{G}{2}\left[\frac{2A + C}{(\varpi^2 + z^2)^{3/2}} - \frac{3(A\varpi^2 + Cz^2)}{(\varpi^2 + z^2)^{5/2}}\right] + \dots . \tag{28}$$

If we consider points not too close to the mass ellipsoid, it is sufficient to retain only the above terms in the expansion. If $z \ll \varpi$, the ϖ component of the gravitational acceleration is, to the first order in z/ϖ,

$$F_\varpi = -\frac{GM}{\varpi^2} - \frac{3G}{2}\frac{(C - A)}{\varpi^4}. \tag{29}$$

A particle in a circular orbit then has an angular velocity about the galactice center given by

$$\Omega_\varpi = \left(-\frac{F_\varpi}{\varpi}\right)^{1/2} = \left(\frac{GM}{\varpi^3}\right)^{1/2}\left(1 + \frac{3}{4}\frac{C - A}{M\varpi^2}\right). \tag{30}$$

The component of the acceleration in the z-direction is, to the first order,

$$F_z = -\frac{GMz}{\varpi^3} - \frac{9G}{2}\frac{(C-A)\,z}{\varpi^5}, \tag{31}$$

and the angular frequency of the oscillation about the galactic plane becomes

$$\Omega_z = \left(-\frac{F_z}{z}\right)^{1/2} = \left(\frac{GM}{\varpi^3}\right)^{1/2}\left(1 + \frac{9}{4}\frac{C-A}{M\varpi^2}\right). \tag{32}$$

After a time t the phase of the rotation lags by an angle

$$a = \frac{3}{2}\left(\frac{GM}{\varpi^3}\right)^{1/2}\frac{C-A}{M\varpi^2}\,t \tag{33}$$

with respect to the phase of the oscillation. This means that the galactocentric longitude of, say, the point of maximum height above the plane $z = 0$ rotates with angular velocity,

$$\omega(\varpi) = \tfrac{3}{2}(GM)^{1/2}\frac{C-A}{M\varpi^{7/2}}, \tag{34}$$

relative to fixed co-ordinates. Since $w(\varpi)$ is a decreasing function of ϖ, this precession is much slower in the outer parts of the Galaxy. The position of maximum elevation above the plane at galactocentric distances ϖ^1 and ϖ^2 will be less than 180° out of phase after a time t, only if

$$|\omega(\varpi_1) - \omega(\varpi_2)|\,t < \pi \tag{35}$$

or

$$\tfrac{3}{2}(GM)^{1/2}\frac{C-A}{M}\left|\frac{1}{\varpi_1^{7/2}} - \frac{1}{\varpi_2^{7/2}}\right| t < \pi . \tag{36}$$

We adopt the values $\varpi_1 = 10$ kpc and $\varpi_2 = 15$ kpc. If the gravitating matter is assumed to be uniformly spread out in an ellipsoid with semiaxes a, a, and $a(1 - e^2)^{1/2}$, we have

$$\frac{C-A}{M} = \tfrac{1}{5}a^2 e^2 . \tag{37}$$

Thus the condition for the distortion to persist for a time t, i.e., for the phase lag to be smaller than π radians, is about

$$a\,e < \left(\frac{10\pi}{3t}\right)^{1/2}\left(\frac{\varpi_1^7}{GM}\right)^{1/4}. \tag{38}$$

With the age of the Galaxy $t = 10^{10}$ years and a galactic mass of $10^{11}\, m_\odot$, we find

$$a\,e < 0.22\varpi_1 = 2.2\text{kpc} . \tag{39}$$

A glance at the models for the mass distribution in the Galaxy, constructed by Schmidt (1958), shows that the effective value of ae is much larger. If we assume $a = 6$ kpc, condition (39) means that the minor semiaxis of the gravitating ellipsoid has to be longer than 5.6 kpc. This is clearly not so.

The process we have described leads to a corrugation of the galactic disk and ultimately changes the original assumed shape beyond recognition. The result would not be a systematic deviaton from the mean galactic plane but rather an increase in the thickness of the galactic disk at large distances. The self-gravitation of the particles, however, tends to resist the formation of corrugations with too short a wave length. Preliminary calculations show that this effect is not large enough to invalidate the above conclusions.

Having thus shown that the distortion in the distribution of the gas cannot be a relic from the time when the Galaxy was formed, we next turn to the alternative possibility that it is produced by some force acting from outside on the Galaxy. Tidal effects produced by other members of the Local Group are negligible (Burke 1957; Kerr *et al.* 1957). We therefore propose to explain the distortion as a hydrodynamic effect, due to the flow of intergalactic gas past the halo.

The center of the Local Group probably lies in the direction $L = 90°$, $b = -25°$, and the Galaxy presumably moves in this direction with a speed of 100 km/sec. Thus the galactic halo moves through the intergalactic gas. Alternatively, we can consider the Galaxy at rest, surrounded by a streaming gas. It is easy to see in a qualitative way what will happen if the gas moves at subsonic speed. Considering the halo to be a sphere, we have high pressure in the direction of motion and low pressure in the perpendicular direction.

From Figure 2 we see that the net effect of the flow coming from the direction $L = 90°$, $b = -25°$ is to press the halo upward around $L = 90°$ and to press the halo downward around $L = 270°$. If, now, as seems plausible, we assume that the magnetic field in the

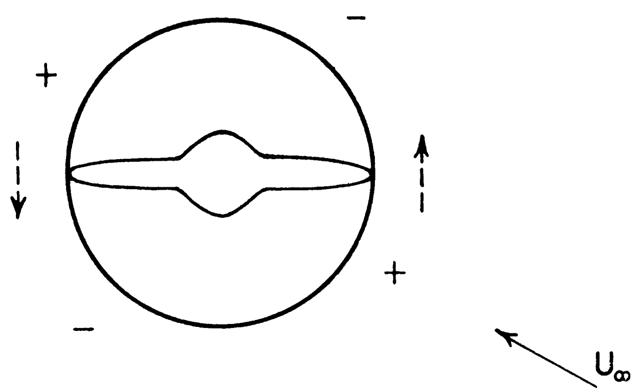

FIG. 2.—The pressure distribution around the halo. The intergalactic gas streams along the Galaxy. The + and − signs indicate region of high and low pressure, respectively. The net effect is an upward force on the right-hand side and the opposite on the other side.

halo transmits the pressure to the gas in the disk, we would expect the disk of gas to be moved upward around $L = 90°$ and downward around $L = 270°$. The gravitational field of the Galaxy provides a restoring force which gradually becomes weaker at larger distances from the galactic center. Thus the distortion should be observable only in the outer parts of the Galaxy. These qualitative predictions are in excellent agreement with the observed situation. We now proceed to discuss the problem in a more quantitative way.

Let us consider the galactic halo to be a sphere. There can be no tangential force between its surface and the gas flowing past it, for, as we have shown in the preceding section, all particles are reflected specularly by the magnetic field.[1] To calculate the variation of the gas pressure over the halo boundary, we should, ideally, solve the equations for the flow of the gas past a gravitating sphere with a smooth surface, but this is a very hard problem.

An earlier calculation showed that heat conduction will be negligible for a motion on this scale, and we therefore assume the flow to be adiabatic. The fact that the gas moves

[1] There will, however, be friction between the halo boundary and the fluid if the magnetic field at the interface has ripples with a wave length much shorter than the mean free path in the fluid. In such a case the drag is proportional to $\overline{\theta^2}$, where θ is a typical angle between the direction of a line of force and the mean tangential direction to the halo surface.

justifies the assumption of an adiabatic relation between pressure and density, made in the foregoing section in the discussion of the halo confinement.

Since there is no tangential surface force, there is no way in which vorticity can be introduced into the fluid, and the flow may be described by a velocity potential. In a coordinate system at rest in the Galaxy the equation of motion integrates to give

$$\tfrac{1}{2} U^2 + \int \frac{dp}{\rho} - \frac{GM}{r} = \text{Const.} \tag{40}$$

For adiabatic flow in a monatomic gas,

$$a^2 = \frac{2}{3} \int \frac{dp}{\rho}; \tag{41}$$

and so

$$U^2 + 3a^2 - \frac{2GM}{r} = U_\infty^2 + 3a_\infty^2, \tag{42}$$

where the suffix ∞ denotes a quantity taken at infinity. Since, further, ρ varies as a^3, the equation of continuity becomes

$$\nabla \cdot (a^3 U) = 0, \tag{43}$$

where we have

$$U = \nabla \phi. \tag{44}$$

It depends on the value of the Mach number, $M = U/a$, whether a solution of this type can satisfy the given boundary conditions. If M exceeds unity, boundary conditions can be imposed only upstream and at infinity. In general, the remaining boundary conditions at the surface of the sphere cannot then be satisfied. A shock wave must therefore appear which separates the sphere and its surroundings from the region of adiabatic flow. The conditions upstream and downstream will then usually be asymmetrical with respect to the center of the sphere.

If M remains less than unity everywhere, a symmetrical flow can exist. This requirement imposes a condition on M_∞. It will be helpful to consider briefly the known pattern of the flow past a non-gravitating sphere (Shapiro 1953). Here it is found that the maximum Mach number occurs on the cross-section of the sphere normal to the mean flow and exceeds unity when $M_\infty > 0.57$. For smaller values of M_∞ there exist adiabatic solutions in which the flow remains subsonic everywhere.

From these calculations a rather useful rule may be obtained for estimating U_0, the maximum flow velocity. Imagine a sphere of radius R placed within a circular cylinder of radius $2R$ down which the gas is flowing. Then, to within 10 per cent accuracy, the value of U_0 is such that

$$\rho_0 U_0 \times \text{area of least cross-section} = \rho_\infty U_\infty \times \text{area of unobstructed cross-section}. \tag{45}$$

Now ρ_0 and U_0 can be found from the energy equation,

$$U_0^2 + 3a_0^2 = U_\infty^2 + 3a_\infty^2, \tag{46}$$

and from the conservation of flux,

$$3\pi R^2 U_0 a_0^3 = 4\pi R^2 U_\infty a_\infty^2. \tag{47}$$

We use a similar rule to estimate u_0 and a_0 for the flow past the gravitating sphere; this time we take the radius of the imaginary cylinder equal to the sum of the radius of the halo and the scale height of the intergalactic gas distribution just outside the halo, which is a conservative estimate, since the resulting value for the radius of the cylinder is even less than $2R$. We have

$$U_0^2 + 3a_0^2 - 2\frac{GM}{R} = U_\infty^2 + 3a_\infty^2, \tag{48}$$

and

$$\pi\left[(R+H)^2 - R^2\right] U_0 a_0^3 = \pi (R+H)^2 U_\infty a_\infty^3, \tag{49}$$

where the scale height is given by

$$H = \frac{kT_0 R^2}{\mu GM} = \left(\frac{3a_0^2 R}{5GM}\right) R. \tag{50}$$

Inserting all numerical values, we obtain

$$U_0 = 60 \text{ km/sec}, \quad M_0 = 0.3. \tag{51}$$

The flow nowhere becomes supersonic, and all boundary conditions can be satisfied. It is readily verified that equations (42)–(44) have a solution in which $\boldsymbol{u}(\boldsymbol{r}) = \boldsymbol{u}(-\boldsymbol{r})$ and $a(\boldsymbol{r}) = a(-\boldsymbol{r})$, provided only that the halo boundary is symmetrical with respect to the galactic center.

The gas exerts its greatest pressure at the stagnation points at the upstream and downstream ends of the halo. Since the pressure varies as a^5, we find that, on the cross-section of the halo which is at right angles to $\boldsymbol{U}_\infty$, the pressure is reduced in the ratio $(a_0/a_1)^5$, where the suffix 1 denotes the value taken at the stagnation point. On the halo boundary GM/R is constant, and it follows from equation (48) that

$$(M_0^2 + 3)\, a_0^2 = 3a_1^2 \tag{52}$$

or

$$\frac{a_0^2}{a_1^2} = \frac{3}{M_0^2 + 3} \simeq 0.97. \tag{53}$$

Thus $(a_0/a_1)^5 \simeq 0.92$. The pressure defect, ΔP is about 8 per cent of the mean pressure on the halo, or about 1×10^{-14} dyne/cm^2. There results a pressure gradient on the halo, which tends to push it away from the stagnation points, and, as indicated above, we assume that this pressure is transmitted to the disk. The resultant force per unit area can displace the gas in the disk to a distance such that, approximately,

$$\Delta P = -F_z l \rho_G \tag{54}$$

where l is the thickness of the galactic gas disk (200 pc) and ρ_G is the typical gas density in the outer parts of the Galaxy. We take $\rho_G = 1.6 \times 10^{-25}$ gm cm^{-3}.

Schmidt's (1958) model calculations give values for F_z everywhere in the Galaxy. From his data we find that the maximum displacement of the plane should be about 100 pc at 12-kpc galactocentric distance and about 300 pc at 14 kpc, values which appear to be somewhat smaller than those given by Oort, Kerr, and Westerhout (1958). However, large uncertainties exist in many of the parameters entering the calculations. Moreover, we may have underestimated the magnitude of the effect by using a static model. In fact, the galactic disk rotates, while the shape of the halo stays fixed in space. The equation of motion for an element of gas in the disk, in the direction normal to the disk has, if rotating co-ordinates are used, the form

$$\ddot{z} + \Omega_z^2 z = -C \cos(\Omega_\varpi t) \tag{55}$$

in our present notation; the solution is

$$z = \frac{C \cos \Omega_\varpi t}{\Omega_z^2 - \Omega_\varpi^2}. \tag{56}$$

The new value of the amplitude is larger by a factor $\Omega_z^2/(\Omega_z^2 - \Omega_\varpi^2)$ than our earlier estimate, in which the inertia term in equation (55) was neglected. We find from Schmidt's data that $\Omega_z^2/\Omega_\varpi^2 \simeq 3$ at 12 kpc distance from the center and 1.5 at 14 kpc The predicted displacements from the plane now become 150 pc at 12 kpc and 900 pc at 14 kpc. We may therefore conclude that the motion of the Galaxy through the intergalactic gas gives a natural explanation for the distortion of the disk of gas in the Galaxy.

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