Static Pressure of Hot Gas: Its Effect on the Gas Disks of Galaxies
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ABSTRACT
The static pressure of the hot gas that fills clusters and groups of galaxies can affect significantly the volume density and thickness of the gas disks in galaxies. In combination with the dynamic pressure, the static pressure allows several observed peculiarities of spiral galaxies surrounded by a hot medium to be explained.

Keywords: gas in clusters of galaxies, star formation in galaxies, interaction of galaxies with ambient medium

1. INTRODUCTION
The interstellar gas in galactic disks is nonuniform in density. However, since the denser regions are generally colder, the pressure fluctuations are considerably smaller than the density fluctuations and we can talk about characteristic equilibrium values of the pressures $P$ at a given galactocentric distance $r$.

In the solar neighborhood, the pressure of the interstellar medium (normalized to the Boltzmann constant $k$) due primarily to the turbulent motions of gas is $\simeq 2 \cdot 10^4 K \cdot cm^{-3}$ (Cox 2005), i.e., $\log P/k \approx 4.3$. Since the pressure of the gas is determined primarily by its mean density, it decreases with galactocentric distance. According to the calculations of the equilibrium pressure of the gas disk in the plane of the stellar disk for self-consistent models of several nearby spiral galaxies, including our Galaxy, (Kasparova and Zasov 2008), the logarithm of the gas pressure $P/k$ in the chosen system of units is $4-5$ at $r = (0.2 - 0.3) R_{25}$ and $3.5-4$ at $r = (0.7 - 0.8) R_{25}$, where $R_{25}$ is the photometric radius of the galaxy. At even larger galactocentric distances, the gas disk expands rapidly and the pressure falls sharply. The gas pressure is particularly low in low-brightness galaxies, where the gas volume density is an order of magnitude lower than that in ordinary spiral galaxies. Nevertheless the star formation, although slow, still holds even there.

If a galaxy is in a cluster, then its interstellar medium is affected by a hot intergalactic gas. For a rapidly moving galaxy and a favorable orientation of its disk with respect to its velocity vector, the dynamic (ram) pressure of the gas, being proportional to $n_e V_c^2$, where $n_e$ is the electron number density of the outer gas and $V_c$ is the relative velocity of the galaxy, should manifest itself. The ram pressure sweeps up the tenuous gas ($HI$)
from the outer regions of galaxies, produces an asymmetry in the HI distribution, and reduces the radius of the region occupied by gas in HI-deficient galaxies (see, e.g., Scodellio and Gavazzi 1993; Cayatte et al. 1994; and references therein). It is much more difficult to sweep up the gas from the inner regions of massive galaxies, where the stellar disk is denser and the potential well produced by the gravitational field of the galaxy is much deeper.

However, the pressure of the surrounding gas at a fairly high temperature can be significant even for a slowly moving galaxy in the hot gas medium. Since the hot gas fills the entire cluster, the speed of sound \( c \approx (P/\rho)^{1/2} \) for it is close to the root-mean-square velocity of the galaxies. Therefore, the static pressure of the intergalactic gas \( P = 2n_e kT \) due to the electron and ion components is close to the mean dynamic pressure. In contrast to the latter, the static pressure acts independently on the galaxy’s velocity relative to the medium or the orientation of its disk; it manifests itself at all galactocentric distances.

The available temperature and density estimates for the intergalactic medium in systems of galaxies show that the static pressure \( P \) of the hot gas is generally comparable to the estimated pressure of the interstellar gas in galactic disks and, hence, can affect significantly the evolution of the gas inside the galaxy. Indeed, the characteristic temperatures of the hot intergalactic gas range from several keV (more than \( 10^7 \) K) in small clusters to 10 keV (more than \( 10^8 \) K) in such clusters as Coma (see, e.g., Arnaud and Evrard 1999; Finoguenov et al. 2001). In rich clusters the gas density decreases with distance from the cluster center according to a law that is usually approximated by the formula

\[
 n(R) = n_0 \left[ 1 + \left( \frac{R}{R_c} \right)^2 \right]^{-3\beta/2},
\]  

(1)

where the parameter \( \beta \approx 0.4 - 0.7 \) depends on the internal structure of the cluster. The core radius \( R_c \) is usually several tens of kpc for small clusters and several hundred kpc for the largest systems (see, e.g., Arnaud and Evrard 1999). At a distance of \((1 - 2) \cdot R_c\), the electron number density is \( n_e \approx 10^{-2} - 10^{-3} \) cm\(^{-3}\). Indeed, in such rich clusters as Coma, A 1795, and A 3112, \( \log P/k > 5 \) within several hundred kpc from the center (Nevalainen et al. 2003). In the Virgo cluster, the particle density at a distance of 100–200 kpc from the center at a temperature \( T \approx 3 \) keV is \( 10^{-3} \) cm\(^{-3}\) (Nulsen and Bohringer 1995), which corresponds to \( \log P/k > 4.5 \). Even at \( n_e \sim 10^{-4} \), which is more characteristic of the cluster as a whole, we obtain \( \log P/k \geq 3.5 - 4 \) for such clusters as Virgo. This value exceeds the expected pressure of the interstellar gas in the outer regions of spiral galaxies. In small clusters containing an X-ray gas, the pressure is of the same order of magnitude as that in large ones: \( kT \approx 1.5 \) keV, \( n_e \approx 10^{-3} \) cm\(^{-3}\) (Dahlem and Thiering 2000).

The same reasoning is also applicable to galaxies in groups, if the latter are filled with an X-ray-emitting gas. In this case, the slightly lower temperature of the hot gas (\( \sim 1 \) keV) is compensated for by the higher particle number density. There exists an HI deficit in galaxies of such groups in spite of their low relative velocity dispersion, and this deficit is more significant than that in X-ray dim groups (Sengupta et al., 2007).
Thus, in systems of various scales the pressure on the gas disk can exceed the internal pressure of the interstellar gas that would exist in the absence of an external action. As a result, the pressure of the interstellar gas in galaxies, particularly in the central regions of clusters, should be, on average, higher and the gas disk thickness $2h$ should be smaller than those for galaxies that undergo no external pressure. The lower the gas density in a galaxy, the stronger the effect of the static pressure. On a qualitative level, this question was discussed previously (Zasov 1987).

2. THE PRESSURE IN THE GAS DISK IN THE PRESENCE OF AN INTERGALACTIC MEDIUM

Consider the increase in gas pressure in the galactic plane quantitatively, in terms of simple equilibrium models. Let us write the hydrostatic equilibrium equation for the gas in the gravitational field of the stellar disk,

$$\frac{dP}{dz} = -g(z) g(z) = -\frac{\mu P(z)}{R} T(z) g(z).$$

(2)

The acceleration $g(z)$ can be expressed in terms of the vertical oscillation frequency $\Omega_z$: $g(z) = z \Omega_z^2 / (1 + |z|/\Delta)$, where $\Delta$ is the vertical scale height of the stellar disk. This formula describes a linear increase in $g(z)$ at small $z$ with its value reaching a constant at large heights $|z| \gg \Delta$. If we restrict ourselves to the approximations $g \propto z$ and $T = T_0 = \text{const}$, then the solution $P = P_0 \exp(-z^2/2h_0^2)$ follows from (2), where we have $h_0^2 = RT_0/\mu \Omega_z^2$, for the vertical scale height $h_0$ of an isothermal gas disk.

We will consider the hot gas that surrounds the disk as an atmosphere with a certain pressure $P_a$ and temperature $T_a$. Let the temperature be $T = T_0 = \text{const}$ in the disk and be also constant at larger heights in the atmosphere, with $T(z \gg h_0) = T_a \gg T_0$, so that the temperature passes from $T_0$ to $T_a$ in some zone at $z > h_0$. Figure 1 illustrates the pressure profiles along $z$ obtained by numerically integrating (2) for various dependences of the temperature $T(z)$ on the vertical coordinate. As we see from the figure, for a fairly sharp increase in temperature at a height $z \sim (2-3)h_0$, the pressure profile ceases to decline with height, reaching a plateau $P = P_a$.

The mean gas pressure in a galactic disk can be represented as

$$\langle P \rangle = P_a + \langle \rho \rangle g h = P_a + \langle \rho \rangle \Omega_z^2 h^2,$$

(3)

where $h$ is the gas scale height in the presence of the atmosphere, the “vertical” acceleration within $h$ due to the stellar disk gravity is assumed to be $g = \Omega_z^2 h$, and the angular brackets $\langle ... \rangle$ denote an average over the $z$ coordinate. Let us denote $\langle \rho \rangle = k_1 \rho_0$ and $\langle P \rangle = k_2 P_0$, where the subscript “0” refers to the quantities in the $z = 0$ disk plane and the coefficients $k_{1,2}$ are determined by the pattern of the vertical density and pressure profiles ($0 < k_{1,2} < 1$).

Let the gas volume density be $\rho_1$ in the absence of an external atmosphere and $\rho_2$ in its presence and the corresponding values for the characteristic gas disk half-thicknesses be $H$ and $h$. Obviously, $H = h = h_0$ and $h < H$ for an isothermal model without and with an atmosphere, respectively.
where $P_0$ is the midplane gas pressure in the absence of the atmosphere.

Substituting (4) into (3), one can obtain

$$x^{n-1} + \frac{\delta}{k_1} x^n - \frac{k_2}{k_1} = 0,$$

(5)

Figure 1. “Vertical” profiles of the pressure (a) and temperature (b) normalized to their values in the $z = 0$ plane for the adopted ratio of the half-thicknesses of the unperturbed gas and stellar disks $h_0/\Delta = 0.2$: 1, in the absence of an atmosphere ($T = \text{const}$); 2 and 3, in the presence of an atmosphere. Curve 3 corresponds to a higher pressure of the atmosphere $P_a$.

We will assume that in the regions where the gas was not swept up from the disk by the ram pressure, its surface density is conserved during compression and, given the mass conservation in the disk, we can write

$$H\varrho_{01} = h\varrho_{02}.$$ .

Taking into account the last relation and restricting ourselves to a polytropic law with a polytropic index $n$, we can write

$$P_0 = P_0 \left( \frac{H}{h} \right)^n,$$

(4)

where $P_0$ is the midplane gas pressure in the absence of the atmosphere.

Substituting (4) into (3), one can obtain

$$x^{n-1} + \frac{\delta}{k_1} x^n - \frac{k_2}{k_1} = 0,$$

(5)
where \( x = h/H \) and \( \delta = P_a/P_0 \). For \( n = 2 \), we find for the ratio of the vertical scale heights in the presence and the absence of an atmosphere:

\[
x = \frac{h}{H} = \frac{1}{2} \left( \sqrt{\frac{k_2}{\delta} + \frac{k_1^2}{\delta^2}} - \frac{k_1}{\delta} \right).
\]

(6)

For \( \delta = 0 \) (there is no hot atmosphere), we will set \( k_1 = k_2 \) to satisfy the condition \( x = 1 \). In the other extreme case, the asymptotics \( x \propto 1/\sqrt{\delta} \) takes place for a large pressure difference (Fig. 2a). The models with a lower value of the index \( n \) seem more realistic. As an example, Fig. 2b shows the ratios \( H/h \) as a function of \( \delta \) for \( n = 1.4 \). We see that the disk becomes appreciably thinner with decreasing \( n \).

Thus, as the external static pressure from the intergalactic hot gas increases, the thickness of the gas disk inside a galaxy can decrease significantly; the proportionality coefficient between \( H \) and \( h \) is determined by the
equation of state for the gas and by the pattern of the vertical density (and pressure) profile, which, in turn, depends on the chosen thermodynamic model of the gas. For instance, as follows from Fig. 2 at an external pressure equal to the unperturbed pressure in the plane of the disk, its thickness decreases and, hence, the gas volume density increases by a factor of $1.5 - 4$. If, however, the pressure of the atmosphere $P_a$ exceeds $P_0$, say, by a factor of 4, then the disk thickness changes by a factor of $2.5 - 10$; the lower values of the above quantities refer to a clearly unrealistic model with a uniform density distribution in disk height. Note, however, that the presence of a magnetic field in the interstellar medium, whose pressure is initially comparable to the interstellar gas pressure, will slightly reduce the gas compression ratio, since in the case of magnetic flux conservation the magnetic pressure, which counteracts the compression, increases as $(H/h)^2$. In the limiting case, if the interstellar gas pressure under strong compression is low compared to the magnetic field pressure, the field strength is $B = \sqrt{8\pi P_a}$. Note that the magnetic field can also greatly reduce the heat conduction at the interface between the two media, isolating the colder gas inside the galaxy from the hot environment. This applies not only to the gas disks of galaxies in clusters, but also to the gas halos of galaxies, which contract, but “survive”, despite being surrounded by a hotter medium (see, e.g., Sun et al. 2007; Vikhlinin et al. 2001).

Thus, one might expect the static pressure of the environment in clusters and groups of galaxies to be capable of increasing the density of the interstellar medium that was not swept up by the dynamic pressure of intergalactic gas by a factor of several. As a result, the gas disks in this case should be, on average, thinner, while the gas midplane volume density should be higher at a fixed column density. In turn, this means a significant increase in star formation rates per unit gas mass and a faster gas exhaustion in the entire disk.

3. DISCUSSION

The static gas pressure is the most universal mechanism of the influence of the ambient medium on a galaxy, since it acts on a gas layer in all cases where the galaxy is surrounded with a hot medium. Below we discuss some data supporting the assumption that the gas disk is compressed by an external pressure in many galaxies, especially if they are located in the inner regions of clusters, although the arguments given remain indirect. Therefore, in each specific case, we cannot rule out the action of other factors either. In particular, hydrodynamic calculations demonstrate that a strong ram pressure may influence the star formation rate not only in the periphery, but also in the inner parts of a galaxy (Kronberger et al., 2008). It is evident that in general case both - dynamic and static pressures - should be considered as a single process. Note however that the efficiency of the ram pressure unlike the static one is proportional to $\rho_{\text{gas}} V_c^2$, hence it is not too effective if the velocity $V_c$ of a galaxy is lower than the mean velocity dispersion of galaxies in a cluster.

(1) Many spiral galaxies in clusters, including $HI$-deficient ones, are actually distinguished by high star formation rates per unit gas mass, i.e., by a short gas exhaustion time scale: star formation is active despite the $HI$ deficit, which is indicative of a high star formation efficiency (Zasov 1987; Scoddegio and Gavazzi 1993; Kennicutt et al. 1984).
It is worth noting that the star formation rates are statistically correlated with the volume gas density: 
\[ SFR \sim \rho_{gas}^n \] where \( n \approx 1 - 2 \) (Schmidt’s law; see Abramova and Zasov, 2008 for a discussion). Therefore, even a twofold increase in gas density accelerates the gas spending on star formation by a factor of 2 – 4. For spiral galaxies, the gas exhaustion time scale \( T_g = \frac{M_{gas}}{SFR} \) is usually several Gyr (Kennicutt 1998, Wong and Blitz 2002; Zasov and Abramova 2006). The dynamic time scale in which the galaxy crosses the densest inner cluster region is of the same order of magnitude. Therefore, an increase in gas density and the corresponding decrease in \( T_g \) as the gas layer is compressed can be an important factor in the evolution of the gas content for cluster galaxies. A decrease in gas density in the outer disk regions should facilitate the sweeping-up of the remnants of the interstellar medium by the flow of intergalactic gas.

In combination with the dynamic pressure and with the minor merging process of galaxies, the static pressure allows us to explain the existence of a large number of disk galaxies with low interstellar gas content (S0-galaxies) in the inner regions of clusters.

(2) The HI-deficient galaxies in clusters are distinguished by a higher (on average) content of the molecular gas with respect to the atomic one (Kenney and Young 1988, 1989); this cannot always be explained by the sweeping-up of HI from the peripheral regions of galaxies and a high \( H_2 \) concentration toward the center. Indeed, the example of spiral galaxies in the inner region of the Virgo cluster shows that an unusually high fraction of the molecular gas is observed even in the inner disk region, where HI is retained, although it can be swept up from the disk periphery (Nakanishi et al. 2006). In the above paper, it was suggested that the external pressure plays a possible role in increasing the amount of molecular gas. Gas compression should actually contribute to the transformation of the atomic gas into the molecular one, since, as analysis of the available observational data shows, the content of the latter strongly correlates with the pressure in the disk midplane (see Kasparova and Zasov 2008; Blitz and Rosolowski 2006; and references therein). However, this effect is so far difficult to test quantitatively.

(3) The example of HI-deficient galaxies in the Virgo cluster shows that, in some cases, the decrease in the total amount of atomic gas in the galaxy is related not so much to a reduction of the region occupied by it, which is natural to associate with the ram pressure, as to a decrease in HI surface density over the entire disk (Cayatte et al. 1994). The latter can be the result of gas compression and its faster “exhaustion”.

(4) The magnetic field enhancement expected when the gas disk in a galaxy is compressed agrees well with the fact that, as was noted by several authors, a significant fraction of the spiral galaxies in clusters are distinguished by a higher intensity of the synchrotron radiation coming from the disk than that for galaxies outside clusters (see Scodeggio and Gavazzi (1993), Reddy and Yin (2004) and references therein).

(5) The role of the static pressure should be most significant for the galaxies located in the inner region of a cluster filled with an X-ray-emitting gas and having low velocities with respect to it, which takes place if the galaxies do not go far away from the cluster center. In this respect, the HI observations in the Pegasus I cluster deserve a special attention. A small, but confidently detectable HI deficit was found for the galaxies
in the central part of this cluster (Levy et al. 2007). Since they have a very low velocity dispersion, the value of \( n_e V^2 \), characterizing the dynamic pressure, is more than two orders of magnitude lower than that in the Coma or Virgo cluster. As a result, the HI deficit cannot be associated with the motion of the galaxies in a gas medium in a standard way. The mean electron number density \( < n_e > \) in a cluster, calculated for the model of a homogeneous sphere, filled with a hot gas with \( T = (0.6 - 3) \cdot 10^7 \text{K} \) is about \( 2 \cdot 10^{-4} \text{cm}^{-3} \) (Canizares et al. 1986). This value is almost equal to the lower limit for the particle number density within 16 arcmin (360 kpc) of the central galaxy of the cluster, NGC 7619, obtained from ROSAT measurements (Trinchieri et al. 1997). At \( T \approx 1 - 2 \text{keV} \), the corresponding gas pressure is \( P \approx (4 - 8) \cdot 10^3 \text{K} \cdot \text{cm}^{-3} \). This static pressure, though it is low, is nevertheless comparable to the interstellar gas pressure in the outer regions of galactic disks (see the Introduction); it exceeds the dynamic pressure on the galaxies in the central part of the cluster, which, based on the estimate \( n_e V^2 = 12 (\text{km/s})^2 \text{cm}^{-3} \) (Levy et al. 2007), is \( \approx 1.5 \cdot 10^3 \text{K} \cdot \text{cm}^{-3} \), by a factor of several. Therefore, in this case, the static pressure of the gas can be more significant.

The external static pressure on the gas disk of a galaxy can be exerted not only by the intergalactic gas, but also by the gas inside the galaxy located in the bulge or inner halo, if the gas has a fairly high density, \( \sim 10^{-2} - 10^{-3} \text{cm}^{-3} \), at a virial temperature of several million degrees. The available estimates of the hot-gas density and temperature in the bulges and halos of galaxies based on their soft X-ray emission are so far few in number. However, they show that a medium with the required density and temperature actually exists at least in some of the massive galaxies, such as M104, NGC 4565, NGC 5746, NGC 4921, and NGC 4911 (Wang 2006; Yao and Wang 2007; Rasmussen et al. 2006; Sun et al. 2007). In these cases, the hot-gas pressure on the disk manifests itself in the same way as the pressure of the intergalactic medium: it compresses the gas in the inner disk region and increases its volume density and, as a sequence, the mass fraction of the molecular gas, which affects the star formation. Indeed, observations show that in the inner regions of such galaxies as M81, M106, and, possibly, M31, where the stellar bulge dominates, the fraction of the molecular gas is considerably higher than could be expected from the semi-empirical dependence of the relative mass of the molecular gas on the gas pressure, if the latter is estimated without taking into account the external medium (Kasparova and Zasov 2008).

Note that at an earlier evolutionary stage of galaxies, their gas disk had a much higher surface density, which then decreased when the bulk of the gas passed into stars. For this reason, the efficiency of the gas sweeping-up by the ram pressure was lower than that at present. Nevertheless, if the pressure of surrounding gas was the same as in the present time, the compression of the gas layer could accelerate the star formation and play an important role in forming the outer regions of stellar disks.

Thus, under some quite realistic conditions, the pressure of the hot medium on the gas disk of a galaxy can be an important factor of its evolution.
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