The Pressure of an Equilibrium Interstellar Medium in Galactic Disks

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Based on an axisymmetric galactic disk model, we estimate the equilibrium gas pressure $P/k$ in the disk plane as a function of the galactocentric distance $R$ for several galaxies (MW, M33, M 51, M 81, M 100, M 101, M 106, and the SMC). For this purpose, we solve a self-consistent system of equations by taking into account the gas self-gravity and the presence of a dark pseudo-isothermal halo. We assume that the turbulent velocity dispersions of the atomic and molecular gases are fixed and that the velocity dispersion of the old stellar disk corresponds to its marginal stability (except for the Galaxy and the SMC). We also consider a model with a constant disk thickness. Of the listed galaxies, the SMC and M 51 have the highest pressure at a given relative radius $R/R_2$, while M 81 has the lowest pressure. The pressure dependence of the relative molecular gas fraction confirms the existence of a positive correlation between these quantities, but it is not so distinct as that obtained previously when the pressure was estimated very roughly $[1, 2]$. This dependence breaks down for the inner regions of M 81 and M 106, probably because the gas pressure has been underestimated in the bulge region. We discuss the possible effects of factors other than the pressure affecting the relative content of molecular gas in the galaxies under consideration.

*Astronomy Letters, 2008, Vol. 34, No. 3, pp. 152-162.*

1. INTRODUCTION

Almost all of the active processes associated with star formation take place in a relatively narrow gaseous layer embedded in the stellar disk. The gaseous layer is inhomogeneous in density and temperature and is more homogeneous in pressure, since a more tenuous medium is simultaneously hotter. For example, our Galaxy shows that the change in gaseous-layer thickness along the disk radius can be well reproduced by assuming a hydrostatic equilibrium (see, e.g., $[3]$). The HI distribution along the $z$ coordinate indicates that the gas density at small $z$ decreases approximately as $\exp(-z^2/h_2^2)$, where $h_2$ is the vertical scale height of the gas distribution, i.e., according to a law expected for an isothermal gaseous layer inside a homogeneous stellar disk, although there is a density excess at large $z$ compared to this simple law $[4, 5]$.

Below, we will assume the galaxy to be axisymmetric and the gaseous disk to be in an equilibrium state in which its thickness is determined by turbulent gas velocities (although it is obvious that the equilibrium condition can be violated in the local regions associated with active processes in the disk).

The mean equilibrium gas pressure at a given galactocentric distance $R$ near the disk plane plays a very important (if not crucial) role in the transition of the gas to molecular form $[6, 1, 2]$. Since the stars are formed in the molecular gas layer, the star formation pattern and rate also depend on the conditions of the gas transition from one phase to another, HI $\leftrightarrow$ H$_2$. Having roughly estimated the turbulent equilibrium pressure of the gaseous layer in several disk galaxies, Blitz and Rosolowsky $[1, 2]$ concluded that the relative molecular gas fraction increases almost linearly with pressure. However, this important conclusion needs to be tested.

To calculate the pressure in galactic disks, the hydrostatic equilibrium and Poisson equations are commonly used and a number of simplifying assumptions are made. For an infinite disk with a vertical gas scale height much smaller than that for the stellar disk, when the contribution from the spheroidal components to the vertical potential gradient is disregarded, the pressure of the medium can be expressed by the formula (see, e.g., $[1]$)

$$P = (2G)^{\frac{1}{2}} \Sigma_{\text{gas}} v_{\text{gas}} (\rho_{\text{star}}^0 + (\frac{\pi}{4} \rho_{\text{gas}})^{\frac{1}{2}}),$$

where $G$ is the gravitational constant, $\Sigma_{\text{gas}}$ is the total surface density of the gas, $v_{\text{gas}}$ is the velocity dispersion of the gas in $z$ coordinate, and $\rho_{\text{star}}$ and $\rho_{\text{gas}}$ are, respectively, the volume densities of the stellar and gaseous components in the disk midplane. For a selfgravitating isothermal stellar disk, the stellar surface density $\Sigma_{\text{star}} = 2 \rho_{\text{star}} h_{\text{star}}$, where the vertical scale height of the stellar disk is $h_{\text{star}} = (v_{\text{star}}^2/2G \rho_{\text{star}})^{\frac{1}{2}}$. Hence follows a simple formula for the equilibrium turbulent pressure if the gas self-gravity is disregarded:

$$P = 0.84 (G \Sigma_{\text{star}})^{\frac{1}{2}} \Sigma_{\text{gas}} v_{\text{gas}} \rho_{\text{gas}}^{\frac{1}{2}} h_{\text{star}}^2.$$
Note that the stellar disk thickness cannot be measured directly and it is generally taken rather arbitrarily. At the same time, $v_{\text{gas}}$ and $h_{\text{star}}$ are assumed to depend weakly on the galactocentric distance $R$ and to change little from galaxy to galaxy. To a first approximation, the gas velocity dispersion is about the same in different galaxies unless the regions of intense star formation or circumnuclear regions are considered. In this case, the turbulent pressure is a function of only the stellar and gas surface densities, i.e., $P(R) \sim \Sigma_{\text{star}}^{0.5} \Sigma_{\text{gas}}(R)$. In this approach, not only the change in stellar disk thickness with $R$, but also the gravitational field of the gas and the dark halo is ignored. Blitz and Rosolowsky argue that this approach gives a pressure estimate with an accuracy of about 10% for $\Sigma_{\text{star}} > 20 \, \text{M}_{\odot}/\text{pc}^2$. However, as we will show below, this error was underestimated significantly.

In this paper, we estimate the equilibrium turbulent pressure of the interstellar medium that corresponds to the mean gas density in the galactic plane at a given $R$ for several disk galaxies. We obtain our estimates through a self-consistent solution of the equations that describe the vertical volume density distributions of the stellar, atomic, and molecular components of a disk that is assumed to be axisymmetric. We take into account the gas self-gravity, the possible change in stellar disk thickness with $R$, and the contribution from the dark halo to the gravitational potential of the galaxy.

### 2. THE SAMPLE OF GALAXIES AND ADOPTED PARAMETERS

To determine the half-thickness of a marginally stable stellar disk, we initially found the epicyclic frequency from the model rotation curve:

$$\omega(R) = 2\Omega \sqrt{\frac{R}{2\Omega} \frac{d\Omega}{dR}}$$

where $\Omega(R) = V(R)/R$ is the angular velocity. For the gravitational stability of a collisionless, infinitely thin homogeneous disk with respect to axisymmetric perturbations, the critical velocity dispersion according to the Toomre criterion is

$$C_{\text{crit}}(R) = \frac{3.366\Sigma_{\text{star}}(R)}{\omega(R)}.$$  \hspace{1cm} (4)

In the general case, the critical radial velocity dispersion is

$$(v_{r})_{\text{star}} = QC_{\text{crit}}.$$  \hspace{1cm} (5)

The parameter $Q$ in our paper is assumed to be constant along the radius and equal to 1.5. Simulations of marginally stable collisionless galactic disks show that this value agrees well (to within $\sim 30\%$) with the numerical results in a large $R$ interval — except for the central region where the bulge dominates and the outermost regions where $Q$ can be twice as high (see, e.g., [12]). Note that an underestimation of $Q$ and, hence, $(v_{r})_{\text{star}}$ means an overestimation of the gas density and pressure.

As residual velocity measurements for old disk stars show, the ratio of the vertical and radial velocity dispersions for most spiral galaxies lies within the range 0.5-0.8; for earlier-type galaxies, this ratio is probably, on average, higher [16], [14]. For all galaxies, we will use the approximate relation:

$$(v_{z})_{\text{star}} = 0.5(v_{r})_{\text{star}}.$$  \hspace{1cm} (6)

For the old disk of our Galaxy and the SMC disk, the vertical stellar velocity dispersions were
In this case, the circular velocity is
\[ v_r = \sqrt{\frac{G M_c}{R_c}} \]
for our Galaxy to be \( v_r \) with the corresponding characteristics.

### Table I: Columns (2) and (3) give the assumed distance to the object in Mpc and its photometric radius \( R_c \) from publications (see the table I for references). For the SMC, observations point to the velocity dispersion, \( v_{\text{rot}} = 27.5 \text{ km/s} \), which changes little with galactocentric distance and is close to the velocity dispersion for the atomic gas (22 km/s). The latter value is atypically high for the galaxies, which is probably due to the interaction between the Magellanic Clouds.

Since the abundance of molecular hydrogen in this galaxy is low with respect to HI, the contribution from H\(_2\) is assumed to be coplanar and axisymmetric, while the gas velocity dispersions are constant with radius. Since the disk thickness is much smaller than the radial density scale length, we ignored the contribution from the radial density inhomogeneity to the potential gradient in \( z \). In a similar way, but using slightly different input parameters and approximations, the disk thicknesses were estimated by Abramova and Zasov [33] for several galaxies common to ours.

### 3. ESTIMATION OF THE EQUILIBRIUM PRESSURE

#### 3.1. The System of Equations

The thicknesses of the disk components, the midplane volume density of the gas, and the corresponding pressure were estimated from the atomic and molecular hydrogen surface densities, which were assumed to be known. To calculate the thickness of a three-component disk (stars, HI, and H\(_2\)) in a general gravitational potential, we used the same method as that applied by Narayan and Jog [3] for our Galaxy. We took into account both the self-gravity of the individual components and the gravitational influence of the halo, which can be significant in the outer disk regions. The main simplification made in this case is that all disks are assumed to be coplanar and axisymmetric, while the HI and H\(_2\) layers are assumed to be isothermal, i.e., the gas velocity dispersions are constant with radius. Since the disk thickness is much smaller than the radial density scale length, we ignored the contribution from the radial density inhomogeneity to the potential gradient in \( z \). In a similar way, but using slightly different input parameters and approximations, the disk thicknesses were estimated by Abramova and Zasov [33] for several galaxies common to ours.
The basic hydrostatic equilibrium equation is

\[
- \frac{\langle (v_z^2) \rangle}{\rho_i} \frac{d\rho_i}{dz} = \sum_{i=1}^{3} \frac{\partial \phi_i}{\partial z} + \frac{\partial \phi_d}{\partial z} \tag{10}
\]

where \( \rho \) is the volume density, \(-\partial \phi / \partial z \) is the force per unit mass along the \( z \) axis, \( \phi \) is the corresponding gravitational potential, the index \( i \) pertains to one of the three disk components (stellar disk, HI, or \( \text{H}_2 \)), and the index \( d \) pertains to the spherical halo.

The Poisson equation for a thin axisymmetric disk is

\[
\sum_{i=1}^{3} \frac{\partial^2 \phi_i}{\partial z^2} = 4\pi G \sum_{i=1}^{3} \rho_i. \tag{11}
\]

The combination of the last two equations leads to an expression for the volume density distribution at a given galactocentric distance:

\[
\frac{d^2 \rho_i}{dz^2} = \frac{\rho_i}{\langle (v_z^2) \rangle} \left[ -4\pi G \sum_{i=1}^{3} \rho_i \frac{\partial^2 \phi_d}{\partial z^2} \right] + \frac{1}{\rho_i} \left( \frac{d\rho_i}{dz} \right), \tag{12}
\]

where the term in the first brackets corresponds to the potential of the three-component disk inside the halo. The influence of the galactic bulge on the disk thickness was disregarded, since the volume density distribution, along with the velocity dispersions of the disk gas and stars in the bulge region, are poorly known. Therefore, the central regions of the galaxies were excluded from our analysis.

The system of equations for the stellar and gaseous components was solved numerically by a fourth-order Runge–Kutta method. The two necessary boundary conditions in the \( z = 0 \) midplane of the disk are

\[ \rho_i = (\rho_0)_i \quad \text{and} \quad \frac{d\rho_i}{dz} = 0. \tag{13} \]

The following normalization condition should be added to this: twice the integral of the volume density over the \( z \) coordinate for each disk component should be equal to the surface (column) density \( \Sigma_i(R) \), which was assumed to be known in the \( R \) interval under consideration.

The volume density of each of the three components was found by the method of iterations. The first step is the simultaneous solution of Eq. (12) for \( \rho_{\text{star}}(z) \) with appropriate boundary conditions at zero gas densities. Subsequently, the problem is solved for \( \rho_{\text{HI}}(z) \) using the stellar volume density obtained at the previous step. At the next step, the system is solved for \( \rho_{\text{H}_2}(z) \) with the known \( \rho_{\text{star}}(z) \) and \( \rho_{\text{HI}}(z) \). Indeed, this is not enough, since the stellar disk was calculated without allowance for the influence of the gas, while molecular hydrogen did not affect the atomic gas density estimate. Therefore, we solved the system of equations successively four more times using the densities calculated in the previous iteration at each step. In this way, we obtained self-consistent solutions for each component in the general gravitational field and, hence, the volume density distributions along \( z \) at a given \( R \).

### 3.2. Pressure Variation Along the Galactic Radius

The gas pressure was determined from the already obtained solutions to the hydrostatic equilibrium and Poisson equations. To within the errors of our iterative calculations (several percent), the equilibrium pressure of the interstellar medium obtained during the solution is equal to the dynamic pressure.
pressure in the disk plane:

$$P = P_{\text{dyn}} = \rho_{\text{HI}} v_{\text{HI}}^2 + \rho_{\text{H}_2} v_{\text{H}_2}^2,$$

(14)

where the contribution from elements heavier than hydrogen (the coefficient 1.38) was taken into account in the gas densities.

We compared the radial pressure variations calculated by our method and from the simplified dependence (2) used by Blitz and Rosolowsky [1], [2]. Since these authors took into account neither the radial variations in the thicknesses of the disk components nor the gas self-gravity, the simplified formula gives a systematic difference (underestimate) of the gas pressure compared to our results. The discrepancy increases with galactocentric distance and ranges from 30% in the inner galactic regions to more than 40% at large $R$, because the gas and the dark halo increase in importance in the outer disk regions.

The resulting estimates of the radial volume density variations for the stellar and gaseous components in the midplane are illustrated in Fig. 1 (a) stellar densities, (b) atomic gas densities, and (c) molecular gas densities. The SMC and MW have the lowest stellar disk volume densities, while M 81 and M 106 have the highest ones. We emphasize once again that the above density estimates for all of the objects, except our Galaxy and the SMC, were obtained by assuming a marginal gravitational stability of the disk and, strictly speaking, give an upper limit for the density.

### 3.3. Our Galaxy

According to our calculations, the stellar volume density near the solar orbit is 0.05 $M_\odot$/pc$^3$, while the atomic and molecular gas densities are, respectively, 0.02 and 0.08 in the same units, corresponding to a total density of all disk components $\approx 0.15 M_\odot$/pc$^3$. The error in the stellar disk surface density, which is known with an accuracy no higher than 30%, introduces the largest uncertainty into the estimate.

Our calculations allow the volume densities of the components to be estimated at any point with coordinates $(R, z)$. Figure 2 shows contours of the volume densities $\rho_{\text{HI}}$ (a) and $\rho_{\text{H}_2}$ (b). In agreement with the observational data (see, e.g., [34]), the atomic gas in our model forms a layer that widens...
FIG. 3: Radial equilibrium pressure distribution for all our galaxies. The solid and dashed lines represent, respectively, the distributions obtained for our main model and by assuming the stellar disk thickness to be constant.

with galactocentric distance, although the model, naturally, cannot reproduce the observed warp of the gas layer at $R > 12$ kpc. The molecular layer is narrower than the atomic one due to its lower velocity dispersion.

Figure 2c presents a contour map that shows the distribution of the molecular gas fraction with respect to the total mass of the gas component, $\rho_{H_2}/(\rho_{HI}+\rho_{H_2})$. We see from the figure that this parameter decreases rapidly with $z$ at Galactocentric distances up to 7 kpc and considerably more slowly at larger distances. However, our model disregards the molecular-to-atomic gas phase transition with increasing $z$. Previously, Imamura and Sofue [34] discussed the possibility of this transition attributable to ultraviolet radiation pressure and density variations. According to the model by these authors, which is based on measuring the vertical molecular gas density profile, the relative molecular fraction $\rho_{H_2}/(\rho_{HI}+\rho_{H_2})$ decreases by half from its maximum value at a distance of $\approx 80$ pc from the disk midplane, while according to our model, this decrease takes place at $\approx 150$ pc. This confirms the possibility of a rapid, on a time scale of less than $10^7$ years, transition of the gas from molecular to atomic form and back. Numerical simulations show [35] that these transitions can actually occur on a short time scale (several million years) in the presence of supersonic turbulence.

Figure 2d illustrates the turbulent gas pressure variations in $z$ coordinate at distances from 4.5 to 14.5 kpc in the disk plane at 2-kpc steps. The heavy line indicates the dependence for the solar distance (8.5 kpc). This scheme clearly illustrates a decrease in the vertical pressure gradient $|dP/dz|$ with Galactocentric distance. As a result, the gas pressure at small $z$ is higher in the inner disk, but the reverse is true at large $z$ and the pressure is higher in the outer Galactic regions.

### 3.4. Radial Gas Pressure Profiles

Parallel with the model of galaxies described above, where the stellar disk thickness changes along $R$ and is determined by the condition for its dynamical stability, we used a simpler model with a constant disk thickness. Since the influence of the gravitational fields from the gas and the dark halo on the stellar disk thickness is ignored in this approach, the problem of estimating the densities and half-thicknesses of the stellar and gaseous components ceases to be completely self-consistent.

As the law $\rho_{\text{star}}(z)$, we took the formula for an equilibrium gravitating isothermal disk.
sulting distributions of the gas volume densities in the outer parts of our Galaxy.

The lowest pressure is in the inner region of M 106, where $\Delta P / k$ decreases approximately by a factor of 1.5 with increasing $(v_z)_{\text{star}}$ and increases by the same factor with decreasing $(v_z)_{\text{star}}$. However, the corresponding changes in gas density and pressure are smaller, no more than 20%. Obviously, the pressure decreases with increasing $(v_z)_{\text{star}}$ and increases with decreasing $(v_z)_{\text{star}}$.

\[ \rho_{\text{star}}(z) = \rho_{\text{star}}(0) \text{sech}^2 \left( \frac{z}{(h_z)_{\text{star}}} \right), \quad (15) \]

where the vertical disk scale height was assumed to be proportional to its radial scale length

\[ (h_z)_{\text{star}} = \frac{(v_z^2)_{\text{star}}}{\pi G \Sigma_{\text{star}}} = 0.2 h_R \quad (16) \]

for all galaxies, except the SMC, and $0.3 h_R$ for the SMC. The half-thicknesses, densities, and pressures of the gaseous components in the gravitational field of the stellar component were determined at the same gas velocity dispersions as those taken in the first (main) model.

The equilibrium pressure distributions (the dependence of $P/k$ on the radial coordinate normalized to the optical radius of the galaxy, $R/R_{25}$) are shown in Fig. 3 for the main model (solid lines) and for the model with a disk of constant thickness (dashed lines). When passing to the latter, the overall pattern of the dependences for most galaxies, in general, changed little; the difference between the pressure estimates does not exceed a factor of one and a half ($\Delta \log (P/k)$ $\geq 0.2$), except for the inner region of M 106, where $\Delta \log (P/k) \approx 0.4$.

In general, the range of gas pressures in the galaxies under consideration is almost two orders of magnitude. Of all the sample galaxies, the SMC has the highest pressure, although the central volume density of the stellar component for this object is lowest (Fig. 1). The high pressure is related both to the high gas content and to the high gas velocity dispersion in this galaxy. The lowest pressure is in the outer parts of our Galaxy.

By varying the input model parameters, we investigated the degree of their influence on the resulting distributions of the gas volume densities and pressures as well as the vertical scale heights of the stellar and gaseous components.

The solution turned out to be most sensitive to the adopted velocity dispersion, primarily for the stellar disk $(v_z)_{\text{star}}$. For illustration, Fig. 4 shows the radial distributions of the volume densities for the three disk components and their vertical scale heights (the dark-gray, light-gray, and lightest colors correspond to $\text{H}_2$, HI, and stars, respectively) calculated, as described above, in terms of the model of a marginally stable disk and after $(v_z)_{\text{star}}$ was increased and decreased by a factor of 1.25 (shaded regions) for the galaxy M 33. The central volume density of the stellar component decreases approximately by a factor of 1.5 with increasing $(v_z)_{\text{star}}$ and increases by the same factor with decreasing $(v_z)_{\text{star}}$. However, the corresponding changes in gas density and pressure are smaller, no more than 20%. Obviously, the pressure decreases with increasing $(v_z)_{\text{star}}$ and increases with decreasing $(v_z)_{\text{star}}$.

3.5. Relationship Between the Pressure and Molecular Gas Content

The pressure is assumed to play a dominant role in the atomic-to-molecular gas phase transition (see the Introduction). Based on the shielding condition for molecular clouds in an UV radiation field, Elmegreen [6] found that the ratio of the molecular gas volume density to the total gas density should be proportional to $P^{2.2} j^{-1}$, where $j$ is the UV radiation density. The simplified pressure estimates by Blitz and Rosolowsky [1], [2] discussed above led to the conclusion that the relative molecular gas fraction $\eta = \Sigma_{\text{H}_2}/\Sigma_{\text{HI}} \propto P^{0.8-0.9}$ for galaxies with various star formation rates. Several galaxies turned out to differ from others by a
higher \( \eta \) at the same pressure. The authors suggested that this was related to the interaction of the galaxies with the ambient medium. One of these galaxies, M 100, belonging to the Virgo cluster, also enters into our paper. However, according to our calculations, it exhibits no anomalous behavior, which also put into question the mentioned interpretation.

Figure 5 shows the dependences \( \eta(P/k) \) for the galaxies of our sample using the two pressure calculation methods described above: by assuming the stellar disk to be marginally stable (left) and assuming its constant thickness (right). Qualitatively, the two models yield similar results. All of the galaxies, except M 81 and M 106, definitely fall on the general dependence: the amount of molecular gas compared to that of atomic one also increases along with equilibrium pressure of the medium. The dependence is best fitted by \( \eta \sim P^k \) (dash-dotted line), where \( k = 1.34 \pm 0.44 \) for the first model (without M 81 and M 106). For comparison, the dots in the figure mark the line that describes the dependence taken from [1], \( \eta \sim P^{0.92} \). The disagreement with our relationship can result not only from the rougher pressure estimates in the cited paper, but also from the inclusion of galactic regions with very high \( \eta > 10 \), which are virtually absent in our dependences. As was shown by Blitz and Rosolowsky [2], a linear dependence more likely reflects the pressure estimation method than the physical relationship between the quantities being compared for \( \eta > 2 \). The reason is that the pressure estimated from the simplified formula is assumed from the outset to be proportional to the atomic gas density and, at large \( \eta > 2 \), to the molecular gas density, which varies over a much wider range than the HI density.

The SMC is absent in the diagram: there is very little molecular gas in this galaxy and it is distributed highly nonuniformly. Because of the low heavy element abundance in the interstellar medium, the conversion factor that relates the CO line intensity to the number of H\(_2\) molecules on the line of sight for the SMC is probably much higher than that commonly assumed for spirals, which makes it difficult to determine the molecular gas mass. It is variously estimated to be from several million M\(_\odot\) to 3 \( \times 10^7 \) M\(_\odot\) [9], but it does not reach 0.1M\(_{\text{HI}}\) even in the latter case, which is an order of magnitude smaller than the expected one, given the high gas pressure (Fig. 3). This discrepancy was also pointed out by Leroy et al. [9]. As in the case of M 33, which also lies below the average line in the \( \eta(P/k) \) diagram, it would be natural to associate this peculiarity with the intensity of the UV radiation, which should play the most important role in these two galaxies due to the low dust content and active star formation.

Note the unusual behavior of M 81 and M 106 in the \( \eta(P/k) \) diagram. It stems from the fact that in the inner regions of these galaxies at distances of several kpc from their cores, the gas surface density ceases to increase or even decreases toward the center (the corresponding segments of the curves for these galaxies in Fig. 5 are marked by dashes). For this reason, the resulting pressure related to both gaseous components remains low. However, since the H\(_2\) density does not exhibit the same deep central “dip” as the HI density, the molecular gas fraction turns out to be high in this case. A similar peculiarity probably also takes place in the Andromeda galaxy (M 31), which is not among the galaxies considered here. Observations show that the HI density in this galaxy also decreases...
toward the center in the inner disk, while the relative molecular gas fraction increases; this effect probably cannot be explained by a change in conversion factor. Note also that although the conversion factor can be lower in circumnuclear galactic regions due to the higher metallicity in the gas, the three mentioned galaxies do not stand out among the remaining ones by their relative oxygen abundance O/H. The fact that the molecular gas content in the inner regions of M33, where the gas exhibits an underabundance of heavy elements, nevertheless, follows the general dependence $\eta(P)$ is indicative of the absence of a close correlation between the gas metallicity and the degree of its molecularization. Similar reasoning is given in for the galaxy IC 10 as well.

Another factor that can affect the $H_2$ abundance and can lead to a high $\eta$ in the inner regions of M31, M81, and M106 is a low UV radiation density. At Galactocentric distances of several kpc, where $\eta$ is large, the intensity of the short-wavelength radiation in M31 and M81 is actually low (see the GALEX images of the galaxies), but this explanation is probably invalid for M106, where the inner region experiences a starburst.

An underestimation of the gas pressure by a factor of 3-10 due to the action of some factors ignored in our simple model can in principle be responsible for the unexpectedly high relative molecular gas content in the inner regions of certain galaxies. Since such galaxies have a large bulge (just as many of the galaxies with a ring-like HI distribution), it would be natural to associate the high relative $H_2$ mass precisely with its presence.

The bulge action on the gas is twofold. First, the bulge produces an additional force that compresses the gas in the disk plane (in our calculations, we took into account only the halo). To a first approximation, the additional bulge-produced pressure is

$$P_b \approx \rho_{gas} g_z h_{gas} \approx \frac{1}{2} \sigma_{gas} V_b^2 h_{gas}/R^2,$$

(17)

where $g_z = GM_b h_{gas}/R^3$ is the $z$ acceleration component attributable to the gravitational field of a bulge with mass $M_b$ and $V_b$ is the circular velocity component associated with the bulge. It is easy to verify that at $h_{gas} \leq 100$ pc and $V_b \leq 200$ km/s, the pressure $P_b/k$ will not exceed significantly $10^4$ K/cm$^3$. Therefore, including the bulge alleviates the problem only slightly, but does not solve it.

The second possibility is the presence of a thermal hot plasma associated with the bulge in which a high gas temperature is supported by old stars (SNI explosions). The presence of a hot gas in the bulges of spiral galaxies manifests itself mainly as soft X-ray emission. Although the observational data are so far rather scarce, a gas with a temperature $(1 \pm 7) \times 10^6$ K was detected in the bulges and halos of several galaxies, including our Galaxy and M31 (see, e.g., 38, 39). Since the pressure inside the cool gaseous layer cannot be lower than the external pressure, a hot gas will play a crucial role at a gas number density of $10^{-2} \div 10^{-3}$ cm$^{-3}$ in the bulge; this can explain the pressure underestimation in the models that disregard the influence of the ambient medium. Probably for the same reason, the molecular gas fraction in lenticular galaxies within several kpc of the center is nevertheless high, despite the low gas content in the disk (see, e.g., 40).

Another factor that is disregarded in axisymmetric disk models is the presence of spiral arms. The gas pressure inside of them is higher and the molecular gas concentration to the spiral arms is a well-established fact. The gas-compressing shock waves cause an increase in the fraction of molecular gas and give rise to giant molecular clouds. A tenuous molecular gas also exists between spiral arms, although it is more difficult to detect (for a discussion, see 41). It is not yet clear how strong the influence of the spiral pattern is on the degree of gas molecularization in the galaxy as a whole. However, in any case, it by no means always plays a significant role. Indeed, in contrast to the morphology of the spiral pattern, the integrated ratios $M_{H_2}/M_{HI}$ in spiral galaxies are almost independent of the morphological type or luminosity of the galaxies. Spiral galaxies in which the bulk of the gas is in molecular form are encountered among the galaxies of all morphological types, except the latest ones 13. Note that the gas-rich M51 and M100 with both an extended spiral pattern and a high relative molecular gas fraction $\eta$ stand out among the galaxies considered in this paper by high fraction of molecular gas. However, the latter agrees well with the higher equilibrium gas pressure in these galaxies (see Fig. 5).

Thus, we have confirmed the dependence of the molecular gas fraction on its mean equilibrium pressure at a given galactocentric distance, although it is not so distinct as the dependence obtained when $P$ is estimated from very simplified formulas. However, such factors disregarded in the model as the external pressure on the disk and the intensity of the UV radiation can also play a significant role in some galaxies.

4. ACKNOWLEDGMENTS

This study was supported by the Russian Foundation for Basic Research (project 07-02-00792).
Translated by V. Astakhov