The Gas Content in Galactic Disks: Correlation with Kinematics

A.V. Zasov¹ and A.A. Smirnova²

¹ Sternberg Astronomical Institute, Universitetskii pr. 13, Moscow, 119992 Russia
² Special Astrophysical Observatory of RAS, Nizhnii Arkhyz, Karachai-Cherkessian Republic, 357147 Russia

Received – June 22, 2004

Abstract. We consider the relationship between the total HI mass in late-type galaxies and the kinematic properties of their disks. The mass $M_{HI}$ for galaxies with a wide variety of properties, from dwarf dIrr galaxies with active star formation to giant low-brightness galaxies, is shown to correlate with the product $V_c R_0$ ($V_c$ is the rotational velocity, and $R_0$ is the radial photometric disks scale length), which characterizes the specific angular momentum of the disk. This relationship, along with the anticorrelation between the relative mass of $HI$ in a galaxy and $V_c$, can be explained in terms of the previously made assumption that the gas density in the disks of most galaxies is maintained at a level close to the threshold (marginal) stability of a gaseous layer to local gravitational instability. In this case, the regulation mechanism of the star formation rate associated with the growth of local gravitational instability in the gaseous layer must play a crucial role in the evolution of the gas content in the galactic disk.

1. INTRODUCTION

Elucidating the mechanisms that determine the current gas content in galactic disks is an outstanding problem. Several processes that are capable to change significantly the total mass of the interstellar medium in galaxies over their lifetimes are known. These include star formation, galactic wind, the ejection of matter by evolved stars, the accretion of intergalactic gas, and the absorption of gas-containing companion galaxies. Undoubtedly, the efficiency of these processes and the extent to which they are balanced vary greatly from one galaxy to another, so the total mass of the gas in a galaxy can both decrease and increase with time during certain evolutionary periods. Still, the main mechanism that determines the current mass of the gas is certainly its consumption for star formation: if we proceed from the current star formation rates (SFRs), then, in most cases, the gas depletion time scale $t_c$ proves to be much smaller than the Hubble age of galaxies (see, e.g., Devereux and Hameed 1997; Bendo et al. 2002; Zasov and Bizyaev 1994; Zasov 1995).

As was first shown by Larson and Tinsley (1978), the color differences between galaxies can be well explained in terms of a difference in the SFR decay rates at the same age of the systems: in redder galaxies, star formation was more intense and has been almost completed. From this point of view, the relative amount of the gas left in the galactic disk must be determined by the star formation efficiency in them (the current SFR per unit gas mass), which is higher in systems with more favorable star formation conditions. Undoubtedly, the current SFR must be affected by the rotational velocity of the gas via both the angular velocity of spiral density waves in the disk and the formation conditions of large-scale gas condensations, which are definitely different in fast and slowly rotating disks.

Actually, however, the situation proves to be not so simple. The current star formation efficiency (or its reciprocal, the gas depletion time scale) was found to correlate rather weakly with other parameters of galaxies. It weakly correlates with the gas mass-to-luminosity ratio for galaxies (Zasov 1995) and shows no clear correlation with the morphological type, the luminosity (Boselli et al. 2002), and the rotational velocity or color of spiral galaxies (Boissier et al. 2001). Both the observed star formation efficiency and the relative gas content in the disk, which is defined as the ratio $M_{HI}/L$, can differ in galaxies of the same morphological type or in galaxies with the same color index by more than an order of magnitude (Verheijen and Sancisi 2001; Boissier et al. 2001).

Hence, it would be natural to expect the total mass of the gas in the disk, which is a derivative of many factors and primarily of the SFR history, to be also insensitive to other parameters of disk galaxies. Nevertheless, several simple relationships prove to exist between the gas mass and galactic disk parameters.

(1) The relationship between $M_{HI}$ and the galaxy size. Although the mass fraction of the gas in a galaxy ($M_{gas}/M_{tot}$) does not correlate with the linear size of the galaxy (McGaugh and de Blok 1997), observations reveal a
close correlation between the total gas mass $M_{HI}$ and the diameter $D$ exhibited by all types of disk galaxies, except the earliest types (SO–Sab) (Hewitt et al. 1983; Broeils and Rhee 1997; Becker et al. 1988; Martin 1998). The form of the relationship is $M_{HI} \sim D^n$, where $n \approx 1.8 - 2$, implying that the mean neutral hydrogen surface density $\langle \sigma_{HI} \rangle$ is approximately constant in various galaxies. If the early-type galaxies are excluded, then $\langle \sigma_{HI} \rangle$ undergoes virtually no systematic changes with galaxy morphological type $T$ and rotational velocity (Karachentsev et al. 1999a, 2004). Low- and high-surface-brightness galaxies also lie on the same $M_{HI}(D)$ relationship (Verheijen and Sancisi 2001).

To explain the approximate constancy of $\langle \sigma_{HI} \rangle$, Shaya and Federman (1987) suggested the transition of the gas to a molecular state when the ionizing radiation is screened by an HI layer where its surface density exceeds a certain threshold value. This mechanism can indeed partly or completely explain the slower decrease in the azimuthally averaged surface density $\langle \sigma_{HI} \rangle(R)$ compared to the molecular gas surface density, but the constancy of the mean gas surface density in galaxies by no means follows from it. Moreover, if the total atomic and molecular gas surface density $\langle \sigma_{HI} + H_2 \rangle$ is taken instead of $\langle \sigma_{HI} \rangle$, then it will prove to also change little along the sequence of morphological types, which by no means follows from the suggested mechanism. This is clearly illustrated by Fig. 1, in which the total gas mass (including the $H_1$, $H_2$, and He masses) is plotted against the optical galaxy diameter for late-type ($T > 3$) galaxies using data from the catalog by Bettoni et al. (2003) (below designated as CISM). Including earlier-type galaxies increases the scatter of points without changing significantly the slope of the relationship.

The correlation of the HI mass with the disk size is particularly pronounced when the radial disks scale length $R_0$ is substituted for the isophotal diameter (Swaters et al. 2002) or when $D_{HI} (= 2R_{HI})$, the size of the gaseous disk bounded by a fairly low threshold gas surface density ($\sigma_{HI} = 1 M_\odot pc^{-2}$) is used as the diameter, within which almost of the HI mass is contained (Verheijen and Sancisi 2001).

(2) The decrease in the relative gas content $M_{HI}/L$ with increasing surface brightness of late type galaxies (Karachentsev et al. 1999a; Mc- Gaugh and de Blok1997; Swaters et al. 2002). This decrease can be easily shown to be a direct result of the relationship $M_{HI} \sim R_0^2$. Indeed, since the disk luminosity $L$ is proportional to $I_0 R_0^2$, where $I_0$ is the disk surface brightness extrapolated to the center, the relationship $M_{HI} \sim R_0^2$ leads to inverse proportionality between $M_{HI}/L$ and $I_0$. For galaxies, whose brightness differ by five magnitudes, the $M_{HI}/L$ ratios must differ by two orders of magnitude, in excellent agreement with the observations of nearby late-type galaxies (see Fig. 5 from Karachentsev et al. 1999a).

(3) The relationship between the galaxy rotational velocity $V_\odot$ and the relative gas mass $M_{HI}/M_{25}$. Here, $M_{25}$ is the indicative mass of the galaxy within its optical radius equal to $V_\odot^2 D/2G$, where $V_\odot$ can be determined from the HI line width corrected for the disk inclination. The faster the galaxy rotation, the lower, on average, its relative gas content (Karachentsev et al. 1999a, 2004; Boissier et al. 2001). As an illustration, Fig. 2 shows the $log(M_{25}/M_{HI}) - log(V_\odot)$ diagram based on the data from the catalog of nearby galaxies by Karachentsev et al. (2004) (where the observational selection effects are probably at a minimum) for Sbc and later-type galaxies. Such a relationship cannot be a simple reflection of different compression ratios of the gas when it passes through spiral density waves, since irregular (including dwarf) galaxies, which constitute a majority among the galaxies of the catalog, also obey it.

(4) The relationship between $M_{HI}$ and the disk specific angular momentum $V_\odot D$ (Zasov 1974; Zasov and Rubtsova 1989). The higher the specific angular momentum, the larger the amount of gas in the galaxy. As we show below, this relationship, which has a simple physical interpretation, is probably the key one. In this paper, we restrict our analysis to the total mass of the gas in late-type galaxies. We show that the relationships listed above can be explained by the fact that the bulk of the gas in galaxies have a surface density close to its threshold value $\sigma_c$ for a gravitationally stable gaseous layer, and that the galaxy diameter correlates with the disk rotational velocity.

2. THE GAS MASS - SPECIFIC ANGULAR MOMENTUM RELATIONSHIP FOR A MARGINALLY STABLE GASEOUS LAYER

Beginning with the classic paper by Quirk(1972), various authors have considered the relationship between the radial gas density distribution in late-type galaxies and the distribution of the critical density $\langle \sigma_c \rangle$ for the growth of local gravitational perturbations. In the simplest case of
a thin gaseous disk in the gravitational field of a galaxy, it is defined by the equation

\[ \sigma_c = c_g \kappa / Q_T \pi G \]  

(1)

Here \( c_g \) is the one-dimensional velocity dispersion of gaseous clouds (6-8 km s\(^{-1}\)), which is commonly assumed to be constant and independent of the morphological type and the galactocentric distance, as direct HI and CO measurements show (except for the galactic circumnuclear regions) (see, e.g., Lewis 1984; Combes et al. 1997); \( \kappa \) is the epicyclic frequency; and \( Q_T > 1 \) is the dimensionless (Toomre) parameter of stability to arbitrarily perturbations in the plane of the disk. In general, its value depends on the shape of the rotation curve and the mass distribution in the disk can be determined analytically or by numerical simulations of the growth of disk instability. For purely radial perturbations of a thin disk, \( Q_T = 1 \). The existing theoretical \( Q_T \) estimates that include nonradial perturbations were obtained only for simplified models of gaseous disks, and their values lie within the range \( Q_T = 1.2-1.7 \) (see Morozov 1985; Polyachenko et al. 1997; Kim and Ostriker 2001; and references therein). The latter authors took into account the magnetic field of the interstellar medium, which does not change the results significantly.

If the gravitational stability of the outer gaseous disk determined for the azimuthally averaged gas density (where \( \sigma < \sigma_c \)) is assumed to be responsible for the sharp reduction in SFR at a certain galactocentric distance \( R_e \) where \( \langle \sigma_{HI} \rangle = \sigma_c \), then a comparison of \( R_e \) with the radius of the outer boundary of the distribution of HI regions corresponds most closely to \( c_g / Q_T \approx 4 \) km s\(^{-1}\) (Martin and Kennicutt 2001); whence it follows that \( Q_T \approx 1.5 - 2 \) at \( c_g \approx 6 - 8 \) km s\(^{-1}\).

Although the question of how closely the boundary of active star formation in galactic disks corresponds to the radius \( R_e \) at which the gas density becomes equal to \( \sigma_c \) is debatable, and this condition is definitely not satisfied in all of the galaxies studied, the it is evident, that the azimuthally averaged density \( \sigma_{HI}(R) \) or \( \sigma_{HI+H_2}(R) \) in most of the S and Irr galaxies is close to \( \sigma_c(R) \) over a wide range of galactocentric distances, differing from it by no more than a factor of 2 (Zasov and Simakov 1989; Martin and Kennicutt 2001; Wong and Blitz 2002; Boissier et al. 2001; Hunter et al. 1998). Including the molecular gas poses a serious problem in estimating the gas mass in the disk. This is because, first, the dependence of the CO-H\(_2\) conversion factor on chemical abundances is known poorly, and, second, direct CO measurements are generally restricted only to the inner galactic region, so when the total mass of the molecular gas is estimated, one has to extrapolate its density to large galactocentric distances. However, the latter is unlikely to play a significant role, since the H\(_2\) fraction decreases with \( R \) (Wong and Blitz 2002).

The situation is alleviated by the fact that the bulk of the observed gas is in the form of HI in most of the galaxies (at least in the late-type ones): the molecular hydrogen mass \( M_{H_2} \), on average, accounts for about 15% of the mass \( M_{HI} \) (Casoli et al. 1998; Boselli et al. 2002). Note, however, that this value may prove to be slightly underestimated: according to the CISM, which combines the \( H_2 \) estimates obtained by various authors by assuming the conversion factor to be constant (2.3x10\(^{20}\) mol K\(^{-1}\) km s\(^{-1}\)), the molecular gas (taking into account helium) accounts for a slightly higher mass fraction (\( \sim 40\% \) of the HI mass), except for the Sd-Irr galaxies that contain a very small amount of molecular gas (Bettoni et al. 2003).

In any case, the inclusion of the molecular gas increases the total mass of the cold gas in spiral galaxies, on average, by no more than a factor of 1.5 (although this factor could be much larger in some of the galaxies), which justifies using the HI mass estimate to characterize the total amount of the gas. The predominance of the atomic gas makes it easier to analyze the evolution of the gaseous component of the disk, since the mass of the molecular gas is known for a much smaller number of galaxies than the HI mass. Here, we do not consider the possibility that reduces the local critical mass by 10-15% and, as it is natural to expect, the effect of the stellar disk decreases with increasing galactocentric distance.

\[^{1}\] The critical density (1) was determined under the assumption of a one-component gaseous disk. The presence of a stellar disk makes the gaseous disk slightly less stable. However, its effect is quantitatively small, since the velocity dispersion of the old disk stars is much higher than that of the gas and since the density of the stellar disk is very low in the outer regions where their values could be comparable. Boissier et al. (2003) showed for several spiral galaxies that including the stellar disk...

\[^{2}\] The gas density is most often higher in the inner galactic region and lower in the outer disk regions than its critical value.
very cold and, hence, unobservable H$_2$ cloudlets in galactic disks can form a layer with such a high total surface density that they produce the effect of hidden mass by contributing significantly to the disk mass (Combes and Pfenniger 1997). This hypothesis encounters serious difficulties in analyzing the gravitational stability of a gaseous layer (Elmegreen 1995) or in dynamical mass estimations for the disks of spiral galaxies (Kranz et al. 2003; Zasov et al. 2004), which do not leave much space for dark matter in the disks.

Let us estimate the gas mass $M$ in a disk, expected if the gas density is close to the critical value over its entire length.

Let the gas density everywhere from the center (R=0) to the radius $R_{HI}$ within which almost all of the HI mass is contained be defined by Eq. (1). We will approximate the circular velocity by a simple function, $V(R) = V_c(R/R_{HI})^n$, where $V_c$ is the rotational velocity on the periphery of the galaxy ($R \sim R_{HI}$), and the constant $n$ can have values for different galaxies from about zero (a plateau on the rotation curve) to unity (rigid-body rotation). In the inner regions of spiral galaxies, the rotation curve is generally more complex in shape, but the bulk of the HI is located in regions far from the center, where $V_c(R) \sim const \ (n \sim 0)$. In irregular galaxies, $0 < n < 1$, while for the least massive systems, the parameter $n$ could be close to unity. For the epicyclic frequency, we have

$$\kappa = 2\Omega [1 + (n - 1)/2]^{1/2} \quad (2)$$

where $\Omega$ is the angular velocity of circular rotation of the disk; whence it follows that the critical gas mass is

$$M_{gas}^c = \int_0^{R_{HI}} 2\pi R \sigma_c(R) dR \quad (3)$$

$$\frac{2^{2/3}}{G} \frac{c_g}{Q_T} (1 + n)^{1/2} V_c R_{HI} \quad (4)$$

The total mass of the gas is related to the masses of the atomic and molecular gases by

$$M_{gas} = 1.4(M_{HI} + M_{H_2}) = \eta^{-1} M_{HI} \quad (5)$$

where $\eta^{-1} \sim 1.4 - 2$ is a coefficient that characterizes the fraction of the molecular gas, helium, and heavier elements in the total mass of the gas (the first value corresponds to a negligible mass of the molecular gas). It follows from (3) and (4) that

$$M_{HI} = \eta M_{gas}^c = \eta 2^{3/2} K (1 + n)^{1/2} V_c R_{HI} / G \quad (6)$$

where $K \equiv c_g/Q_T$. Given the uncertainties in the $Q_T$ and $c_g$ estimates (see above), $K$ may be assumed to lie within the range 3.5 - 6.5 km s$^{-1}$.

Since the resulting estimate depends weakly on the parameter $n$ (the largest uncertainty is associated with the ratio $c_g/Q_T$ and with the assumption of its constancy along the radius), we assume below that $n = 0$, which corresponds to the same rotational velocity at all $R$. In this case,

$$M_{HI} = 2^{3/2} \eta \frac{K}{G} V_c R_{HI}. \quad (7)$$

A relation similar to (5) (but with a different numerical value of the proportionality coefficient) can also be written for the case where the photometric radius $R_{25}$, which, on average, is a factor of 1.7-1.8 smaller than $R_{HI}$ for both spiral and irregular galaxies (Broeils and Rhee 1997; Swaters et al. 2002), is used instead of $R_{HI}$ as the upper integration limit in Eq. (3). Therefore, Eq. (6), to within numerical coefficients, describes the previously reached conclusion (Zasov 1974; Zasov and Rubtsova 1989) that the total mass of the gas at its threshold density is proportional to its specific angular momentum $DV_c$, where $D$ is the optical diameter of the galaxy. This relationship is actually in good agreement with the observations, both for single galaxies and for galaxies in pairs (Zasov 1974; Zasov and Rubtsova 1989; Zasov and Sulentic 1994; Karachentsev et al. 1999a, 2004). To check how universal this conclusion is for various galaxies and to quantitatively compare $M_{HI}$ and $M_{HI}^c$ below we consider several samples of late-type galaxies with widely differing parameters - from clumpy irregular galaxies with bright sites of star formation to Malin-1-like galaxies of extremely low disk surface brightness with very low SFRs.

The optical isophotal diameter is of little use for this purpose, since it offers no possibility of comparing galaxies with different surface brightnesses: the lower the surface brightness of the disk with the same radial scale length, the smaller its isophotal diameter. Therefore, it would be more appropriate to compare galaxies by using the radial disk scale length $R_0$ rather than the optical diameter. On average, $R_{HI} \approx 5.4 R_0$ for both irregular and spiral galaxies (Swaters et al. 2002). Below, we use this relationship to estimate $M_{HI}^c$.

### 3. SAMPLES OF GALAXIES

In this paper, we consider several different samples of late-type galaxies with known hydrogen masses $M_{HI}$, rotational velocities $V_c$ (determined in most cases from the HI line width), and photometric radial scale lengths $R_0$: dwarf irregular (dIrr) galaxies, HI-rich late-type galaxies, UMa cluster galaxies, clumpy irregular (cIrr) galaxies, which were included in the atlases of interacting systems by Vorontsov-Vel’yaminov (1959, 1977) due to their peculiar appearance, edge-on late-type galaxies, and low-surface-brightness galaxies including three objects of extreme Malin-1-type. If required, the distances to galaxies with significant systemic velocities were reduced to the Hubble constant $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$. For nearby dwarf galaxies, we used distance taken from original works.

Let us consider the samples separately.

(1) Galaxies that morphologically belong to late-type spirals or irregulars with an absolute magnitude of -18 or fainter and line-of-sight velocities lower than 3000 km s$^{-1}$.
constituted the sample of dwarf galaxies. These are non-interacting systems: they have no apparent companions within 30′ whose velocities differ by less than 500 km s\(^{-1}\) from the velocity of the galaxy. All of the parameters, except the optical isophotal radius \(R_{25}\), were taken from the paper by van Zee (2001). The radius was calculated from the assumed distance and the angular diameter \(D_{25}\) (the latter was taken from the LEDA database).

(2) Late-type galaxies with an absolute magnitude of \(-17\) or fainter and a high flux density in the HI line \((S_{\text{HI}} > 200\ \text{mJy})\) constituted the second sample of dwarf galaxies. Data for them were taken from the paper by Swaters et al. (2002). With the exception of several galaxies, all of them lie at distances less than 25 Mpc.

(3) Galaxies from the catalog by Vorontsov-Vel’yaminov (1959, 1977) whose peculiar shapes are very likely to be attributable not to the system multiplicity, but to the clumpy distribution of bright star-forming regions constituted the sample of clumpy irregular (cIrr) galaxies. Several tens of such galaxies were identified, but the radial disk scale length could be estimated only for several objects: due to the presence of bright condensations, the surface brightness of the disks in such galaxies by no means can be always described by an exponential law. Data for these galaxies were taken from the literature (Patterson and Thuan 1996; Yasuda et al. 1997; Martin 1998; Bremnes et al. 1999; Iglesias-Paramo and Vilchez 1999; Makarova 1999; Thuan et al. 1999; Barazza et al. 2001; Cairós et al. 2001a, 2001b; Shapley et al. 2001; Pustilnik et al. 2003) and from the HyperLeda database (http://www-obs.univ-lyon1.fr/hypercat/).

(4) Late-type spirals from the UMa open cluster that differ widely in surface brightness constituted the sample of normal spiral galaxies. Data for these galaxies were taken from the paper by de Block (1996). The central brightness of the disks in these galaxies is \(\mu_0(B) \geq 23^{m}/\sigma''\). The sample was supplemented by three objects with extremely low surface brightnesses: Malin 1, F568-6, and 1226+0105. All of the data for the latter were taken from the paper by Sprayberry et al. (1993) and reduced to \(H_0 = 75\ \text{km s}^{-1}\ \text{Mpc}^{-1}\).

(5) The sample of low-surface-brightness galaxies was taken from the paper by de Block (1996). The central brightness of the disks in these galaxies is \(\mu_0(B) \geq 23^{m}/\sigma''\). The sample was supplemented by three objects with extremely low surface brightnesses: Malin 1, F568-6, and 1226+0105. All of the data for the latter were taken from the paper by Sprayberry et al. (1993) and reduced to \(H_0 = 75\ \text{km s}^{-1}\ \text{Mpc}^{-1}\).

(6) The sample of edge-on spiral galaxies was drawn from the RFGC catalog (Karachentsev et al. 1999b). The latest version of this catalog contains 4236 galaxies distributed over the entire sky with apparent axial ratios \(a/b \geq 7\) and angular diameters \(a \geq 0′.6\). Sc-Sd galaxies with small bulges constitute the bulk of the catalog. The RFGC objects are rich in gas and are easily detectable in the 21-cm HI line.

No correction for the projection is required for them when estimating the rotational velocity of the outer disk. More importantly, the selection criteria make the sample homogeneous in the structure of its constituent galaxies. HI data for the galaxies are given in the paper by Karachentsev and Smirnova (2002). The radial disk scale lengths for the edge-on galaxies were taken from the papers by Bizyaev (2000), Bizyaev and Mitronova (2002), and Kregel et al. (2002). Since \(R_0\) determined for the B band was used in other samples, the disk scale length for the edge-on galaxies obtained in the near infrared was also reduced to the B band using the relations

\[
R_{0B} = 1.44R_{0I}, \quad R_{0B} = 1.65R_{0K},
\]

where \(R_{0B}, R_{0K}\), and \(R_{0I}\) are the radial disk scale lengths in the B, K, and I bands, respectively (de Grijs 1998).

4. THE UNIVERSALITY OF THE GAS MASS-SPECIFIC ANGULAR MOMENTUM RELATIONSHIP

Since the samples are heterogeneous, the \(M_{HI}\) and \(R_0\) estimates of interest may have various systematic errors. Nevertheless, all of the samples show similar relationships, although some of them are noticeably displaced from one another in the diagrams.

Figure 3 shows the relationships between the neutral hydrogen mass and the products \(R_2V_c\) (Fig. 3a) and \(R_0V_c\) (Fig. 3b) whose existence follows from the assumption that the mass of the gas is close (or proportional) to the critical value for gravitational stability (see the section 2). Both these products characterize the specific angular momentum of rotating disks. The diagrams reveal a correlation between the quantities being compared, which, as would be expected, becomes more pronounced when using the radial scale length \(R_0\).

If these relationships were a simple reflection of the already discussed size-\(HI\) mass relation, then including the rotational velocity would blur them appreciably. In fact, although \(M_{HI}\) correlates both with \(R_0\) and (slightly worse) with \(V_c\) (Figs. 4a and 4b), the correlation coefficient between the HI mass and the product of these quantities is as high (if not higher) as that between the HI mass and the kinematic parameters of the gaseous disk. The correlation coefficients \(r\) and the parameters of the linear dependences \(Y = a + bX\) considered in this section are given in the table. The coefficient \(b_t\) is the mean slope \(Y/X\) of two regression lines: \(Y(X)\) and \(X(Y)\).

The band bounded by the parallel lines in Fig. 3b describes the expected relationship between the critical mass \(M_{HI}\) and \(V_cR_0\) for the case where the total mass of the gas in the disk (which was assumed here to be proportional to \(M_{HI}\)) is close to its critical value: \(M_{gas} = M_{gas}^c\) (see (6)). The band width characterizes the uncertainty in the coefficients in the equation (see the second section) and primarily in the coefficient \(K\), the ratio of the gas velocity dispersion to the Toomre parameter. The most probable values of \(M_{HI}^c\) correspond to the dashed line drawn
Fig. 3. HI mass-specific angular momentum diagram for galaxies of different samples. The logarithm of the product $V_c R_{25}$ (top figure) or $V_c R_0$ (bottom figure) (where $V_c$ is the rotational velocity (km s$^{-1}$), $R_{25}$ is the optical radius of the galaxy (kpc), and $R_0$ is the photometric radial disk scale length), is along the horizontal axis; the logarithm of the HI mass (in solar units) is along the vertical axis: (1) dwarf galaxies with quiescent star formation, (2) hydrogen-rich galaxies, (3) clumpy irregular (cIrr) galaxies, (4) low-surface-brightness galaxies, (5) edge-on late-type spirals, (6) UMa cluster spirals, and (7) three Malin-1 type galaxies.

Fig. 4. (Top) Radial disks scale length $R_0$ - HI mass diagram; (Bottom) rotational velocity $V_c$ - HI mass diagram. The mean gas surface density in them slightly exceeds the critical value calculated with the assumed values of $c_g/Q_T$ (see the section 2).

The agreement between the theoretically expected (for a marginally stable disk) and observed HI masses (Figs. 3b and 5), along with the relatively small number of galaxies located above the highlighted band in Fig. 3b, in which the hydrogen mass evidently exceeds $M_{H_I}^c$, suggest that the gravitational stability condition for a gaseous layer is an important factor that determines the amount of gas at the current epoch and, hence, regulates the star formation efficiency and the gas depletion rate. If we exclude the galaxies chosen by a high HI flux density (open asterisk),

through the center of the band. As we see from Fig. 3b, the overwhelming majority of points in the diagram lie within or slightly below the uncertainty band. The relatively large scatter in the positions of cIrr galaxies (triangles) and edge-on galaxies (filled circles) in the log $M_{HI}$ - log($V_{rot}R_0$) diagram is probably attributable to the larger errors in the radial scale lengths of their disks. The $HI$ mass also deviates significantly from the expected value for several most slowly rotating gas-poor dwarf galaxies (in the lower part of the diagram).

Some of the gas-rich dwarf galaxies chosen by a high flux density in the HI line (open stars) are located slightly above, but also parallel to the relationship for $M_{HI}^c$. The

5. DISCUSSION AND CONCLUSIONS

The estimates of the observed hydrogen mass and the most probable critical mass $M_{HI}^c$ (corresponding to the central line of the band in Fig. 3b) for the galaxies under consideration are compared in Fig. 5. Like the diagram in Fig. 3b, the diagram in Fig. 5 clearly reveals a close correlation between the observed gas content in the galaxies and the kinematic parameters of their disks.
then, on average, the total HI mass in the galaxies under consideration proves to be slightly lower than \( M'_{HI} \) (by a factor of 1.5-2). This is probably the result of a low (compared to the critical value) gas density in the outer disk regions, beyond \( D_{25} \), where a tangible fraction of the total HI mass is contained (Broeils and Rhee 1997).

The correspondence of the HI mass to its expected critical value of \( M_{HI}^c \) (and of the total gas mass to its critical value of \( M_{gas}^c \)) for late-type galaxies can be naturally explained by assuming that during the evolution of the galaxy, when the mean gas density decreased to a level close to the critical one for gravitational stability of the gaseous layer, the gas depletion slowed down significantly, and, as a result, most of the galaxies could preserve an amount of gas close to (or slightly smaller than) \( M'_{gas} \) up to the present time. This conclusion applies to most of the galaxies of all the samples considered, including the extremely low-brightness Malin-1-type galaxies, since they lie on the general relationship (Fig. 3b). The gas content in these unusual galaxies proved to be close to the expected values for disks with enormous angular momentum. The star formation rates and efficiency in their disks, as well as in the disks of normal brightness galaxies, must have been decreased when the gas density reduced below the critical level. However, this does not rule out the possibility that different initial formation conditions or a lower initial density of the gaseous disk are responsible for their low brightness.

The approximate proportionality between the rotational velocity \( V_c \) and the size of galaxies that was pointed out by several authors (Tully and Fisher 1977; Karachentsev et al. 1999a) can explain why the gas mass proportional to \( V_c R_{25} \) changes linearly with the square of the galactic disk size (the mean HI surface density is almost constant). The most clear and almost linear relationship between the rotational velocity and the optical size of galaxies was found for a homogeneous sample of nearby galaxies: \( logD \sim \langle 0.99 \pm 0.06 \rangle logV_c \) (Karachentsev et al. 1999a).

Another important conclusion also follows from the existence of a linear relationship between the observed mass \( M_{HI} \) and \( M_{HI}' \): galaxies with slowly rotating disks must, on average, possess a higher relative gas mass, i.e., have a lower ratio of the total (indicative) mass \( M_{25} \) within the photometric radius to the total HI mass. Indeed, since the photometric radius is proportional to \( R_0 \) and since the total mass \( M_{25} \sim V_c^2 R_0 \), the relation \( M_{25}/M_{HI} \sim V_c \) follows from the condition \( M_{HI} \sim V_c R_0 \). This conclusion is in a good agreement with the observational data (Fig. 2).

Thus, the observed gas content in late-type galaxies reflects a similar (for most of them) pattern of evolutionary change of the gas mass in the disk. The gravitational instability of the gaseous layer must play a crucial role in this evolution. The growth of instability probably facilitated to the enhancement of star formation and to the fast gas depletion at the initial (violent) evolutionary stage of the galactic disk. Note that at the early stage the density of the gaseous disk exceeded significantly the critical value calculated for the current gas velocity dispersion reflecting the quiescent pattern of star formation.

This conclusion should be valid for galaxies with various diameters, rotational velocities, current SFRs rates, and disk surface brightnesses.

In this paper, we have not considered early-type (S0-Sab) disk galaxies, which contain little gas at the same sizes and rotational velocities as those of late-type galaxies. These systems must have a slightly different star formation history; they have lost a significant fraction of their gas either through external factors (e.g., due to the gas being swept up as it moved in the intergalactic medium of the cluster) or through internal processes that provided active star formation even when the gas density decreased below the critical level for large-scale gravitational instability.

### ACKNOWLEDGMENTS

We wish to thank I. D. Karachentsev for a discussion of the work and for presenting the paper (Karachentsev et al. 2004) before its publication. Authors also thank Dr. G. Galletta for the electronic version of CISM. This work was supported in part by the Russian Foundation for Basic Research (project no. 04-02-16518).

---

**Table 1.** Correlation coefficients and parameters of the linear dependences \( Y=aX+b \)

| X, Y          | r    | a     | b     | b_5  |
|---------------|------|-------|-------|------|
| \( log V_c R_{25}, log M_{HI} \) | 0.8  | 7.25 ± 0.10 | 0.71 ± 0.04 | 0.94 ± 0.07 |
| \( log V_c R_0, log M_{HI} \) | 0.9  | 7.05 ± 0.07 | 0.91 ± 0.03 | 1.05 ± 0.04 |
| \( R_0, log M_{HI} \) | 0.9  | 8.63 ± 0.03 | 1.45 ± 0.06 | 1.69 ± 0.08 |
| \( log V_c, log M_{HI} \) | 0.7  | 5.57 ± 0.22 | 1.79 ± 0.11 | 2.52 ± 0.24 |
References

F. D. Barazza, B. Binggeli, and P. Prugniel, Astron. Astrophys. 373, 12 (2001).
R. Becker, U. Mebold, K. Reif, et al., Astron. Astrophys. 203, 21 (1988).
G. J. Bendo, R. D. Joseph, M. Wells, et al., Astron. J. 124, 1380 (2002).
D. Bettoni, G. Galletta, and S. Garcia-Burillo, Astron. Astrophys. 405, 5 (2003).
D. Bizyaev, astro-ph/0007242 (2000).
D. Bizyaev and S. Mitronova, Astron. Astrophys. 389, 795 (2002).
S. Boissier, A. Boselli, N. Prantzos, et al., MNRAS. 321, 733 (2001).
S. Boissier, N. Prantzos, A. Boselli, and G. Gavazzi, MNRAS. 346, 1215 (2003).
A. Boselli, J. Lequeux, and G. Gavazzi, Astron. Astrophys. 384, 33 (2002).
T. Bremnes, B. Binggeli, and P. Prugniel, Astron. Astrophys. Suppl. Ser. 137, 337 (1999).
A. H. Broeils and M.-H. Rhee, Astron. Astrophys. 324, 877 (1997).
L. Cairos, N. Caon, J. Vilchez, et al., Astrophys. J. Suppl. Ser. 136, 393 (2001b).
L. Cairos, J. Vilchez, J. Gonzalez Perez, et al., Astrophys. J. Suppl. Ser. 133, 321 (2001a).
F. Casoli, S. Sauty, M. Gerin, et al., Astron. Astrophys. 331, 451 (1998).
F. Combes and J.-F. Becquaert, Astron. Astrophys. 326, 554 (1997).
F. Combes and D. Pfenniger, Astron. Astrophys. 327, 453 (1997).
W. J.G. de Block, S. S. McGaugh, and J.M. van der Hulst, MNRAS 283, 18 (1996).
R. de Grijs, MNRAS 299, 595 (1998).
N. Devereux and S. Haneef, Astron. J. 113, 599 (1997).
B. G. Elmegreen, MNRAS 275, 944 (1995).
J. Hewitt, M. Haynes, and R. Giovanelli, Astron. J. 88, 272 (1983).
D. A. Hunter, B. G. Elmegreen, and A. L. Baker, Astrophys. J. 493, 595 (1998).
J. Iglesias-Paramo and J. M. Vilchez, Astrophys. J. 518, 94 (1999).
I. D. Karachentsev, V. E. Karachentseva, W. K. Huchtheimer, et al., Astron. J. 127, 2031 (2004).
I. Karachentsev, V. Karachentseva, Y. Kudrya, et al., Bull. SAO 47, 5 (1999b).
I. D. Karachentsev, D. I. Makarov, and W. K. Huchtheimer, Astron. Astrophys. Suppl. Ser. 139, 97 (1999a).
I. D. Karachentsev and A. V. Smirnova, Astrofiz. 45, 448 (2002).
W.-T. Kim and E. Ostrik er, Astrophys. J. 559, 70 (2001).
T. Kranz, A. Slyz, and H. W. Rix, Astrophys. J. 586, 143 (2003).
M. Kregel, P. van der Kruit, and R. de Grijs, MNRAS 334, 646 (2002).
R. Larson and B. Tinsley, Astrophys. J. 219, 46 (1978).
B. Lewis, Astrophys. J. 285, 453 (1984).
L. Makarova, Astron. Astrophys.Suppl. Set. 139, 491 (1999).
M.C. Martin, Astron. Astrophys. Suppl. Ser. 131, 77 (1998).
C. Martin and R. Kennicutt, Astrophys. J. 555, 301 (2001).
S. McGaugh S. and W. J. G. de Blok, Astrophys. J. 481, 689 (1997).
A. G. Morozov, Sov. Astron. 29, 120 (1985).
R. Patterson and T. Thuan, Astrophys. J. Suppl. Ser. 107, 103 (1996).
D. L. Polyachenko, E. V. Polyachenko, and A. V. Strel’nikov, Astron. Lett. 23, 483 (1997).
S. Pustilnik, A. Zasov, A. Kniazev, et al., Astron. Astrophys. 400, 841 (2003).
W. Quirk, Astrophys. J. Lett. 176, L9 (1972).
A. Shapley, G. Fabbiano, and P. Eskridge, Astrophys. J. Suppl. Ser. 137, 139 (2001).
E. J. Shaya and S. R. Federman, Astrophys. J. 319, 76 (1987).
D. Sprayberry, C. D. Impey, M. J. Irwin, et al., Astrophys. J. 417, 114 (1993).
R. A. Swaters, T. S. van Albada, J. M. van der Hulst, and R. Sancisi, Astron. Astrophys. 390, 829 (2002).
T. X. Thuan, V. A. Lipovetsky, J.-M. Martin, and S. A. Pustilnik, Astron. Astrophys. Suppl. Ser. 139, 1 (1999).
R. B. Tully and J. R. Fisher, Astron. Astrophys. 54, 661 (1977).
M. A. W. Verheijen and R. Sancisi, Astron. Astrophys. 370, 765 (2001).
L. van Zee, Astron. J. 121, 2003 (2001).
B. A. Vorontsov-Velyaminov, Atlas and Catalogs of Interacting Galaxies (Mosk. Gos. Univ, Moscow, 1959)[in Russian].
B. A. Vorontsov-Velyaminov, Astron. Astrophys. 28, 1 (1977).
T. Wong and L. Blitz, Astrophys. J. 569, 157 (2002).
N. Yasuda, M. Fukugita, and S. Okamura, Astrophys. J. Suppl. Ser. 108, 417 (1997).
A. V. Zasov, Sov. Astron. 18, 730 (1974).
A. V. Zasov, Astron. Lett. 21, 652 (1995).
A. V. Zasov and D. V. Bizyaev, Publ. Astron. Soc.Pacif 66, 73 (1994).
A. V. Zasov, A. V. Khoperskov, and N. V. Tyurina, Astron. Lett. 30, 593 (2004).
A. V. Zasov and T. V. Rubtsov, Sov. Astron. Lett. 15, 51 (1989).
A. V. Zasov and S. G. Simakova, Astron. 29, 518(1989).
A. V. Zasov and J. Sulentic, Astrophys. J. 430, 179 (1994).