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N sub H2 = 2.8 x 10(exp 20) I sub CO

Radial Profiles of Gas in Late-Type Disk Galaxies

Curtis Struck-Marcell, Iowa State University

I. Review of Published Data

The azimuthally averaged HI distribution, and the total gas density distribution derived from HI and CO observations (and assuming $N_{H2} = 2.8 \times 10^{20} I_{CO}$) as a function of radius in several nearby, early-type disks are examined in this study.

A. $\Sigma \propto 1/r$ where the Rotation Curve is Flat

First pointed out by Quirk (1972), and recently discussed by Kennicutt (1989) this conclusion is evident in the gas distributions considered here, and in the data of Wevers' (1984) thesis. For example, the figure shows the deviation of the azimuthally averaged HI surface density profiles from a best-fit 1/r profile in Wevers' galaxies. Only data from positions with circular velocities within 5% of the average value in the flat part of the rotation curve are plotted, only those galaxies with more than 3 such points were included. The curve for NGC 628 also includes the molecular gas observed by Adler and Lizst (1989). For the other sample galaxies the molecular gas either lies interior to the flat part of the rotation curve or a CO distribution has not been published. It is apparent that most of the data fall within about 25% of the mean 1/r profile, except in the outermost parts of some galaxies. The larger surface density deviations in these outer regions frequently correlate with deviations from flatness in the rotation curve.

B. The Gas Distribution in the Inner Disk is More Complex

The available data for the inner regions of the disks are more sparse and their interpretation is more problematic. We can only make a few tentative generalizations:

1. When the central gas surface density is high (e.g. $\Sigma > 30$ solar masses/pc^2) the 1/r profile continues from the outer regions to deep into the central regions (e.g. IC 342, NGC 5055, NGC 6946).
2. In the other galaxies there is still a central peak in $\Sigma(r)$. In the cases considered here, this peak is clearest in M33 and NGC 2403, where it lies within the region with $v_\theta < 60$ km/s.
3. If the central peak is well interior to the $\Sigma \propto 1/r$ region, then there is a flat, $\Sigma \propto$ constant, transition region (M33, NGC 2403). In NGC 628 the center may be primarily of this flat form, since the central rise is very modest.

II. Theoretical Considerations and Constraints

A. Azimuthally Averaged Hydrostatic Equilibrium (for a continuum gas)

We have *accretion* disk equations like those in the review of Pringle (1981).

1. Mass Continuity, implies $\partial\Sigma/\partial t = 0$, radial velocity $v_r = 0$, and self-diffusion term $\partial^2(r\Sigma)/\partial r^2 = 0$, which yields $\Sigma = a/r + b$, with a,b = constant.
2. Equation of State: Isothermal cloud gas, with sound speed c = constant, may be an adequate approximation.
3. Momentum Transport:

a) Radial Force Balance (in a potential dominated by collisionless matter). The azimuthally averaged pressure gradient force is

$$\frac{1}{r\Sigma}\frac{d}{dr}(rP) = \frac{1}{r\Sigma}\frac{d}{dr}(r\Sigma c^2)$$

Case i) $\Sigma \propto 1/r$. The pressure gradient force is zero, and centrifugal force balances gravity, just as for the stars.

Case ii) Σ = constant. The averaged pressure gradient force goes as 1/r. In the flat rotation curve region, v_θ = constant >> c, and both gravity and centrifugal force also go as 1/r, so pressure is negligible throughout the region. In a solid body region, $v_\theta \propto r$, so as r decreases the pressure increases relative to the centrifugal force.

b) Azimuthal Force Balance The only force is viscosity, so in equilibrium it must be zero, then,

$$\nu \Sigma r^3 \frac{\partial}{\partial r}\left(\frac{v_\theta}{r}\right) = \text{constant},$$

which gives a relation between Σ and v_θ. E.g.,
if v_θ = constant, then $\nu\Sigma r$ = constant (or $\Sigma \propto 1/r$ for ν = constant).
if $v_\theta \propto r$, then $\partial(v_\theta/r)/\partial r = 0$, and Σ is unrestricted.
if Σ = constant, then either $v_\theta \propto r$ or $v_\theta \propto 1/r$ (unphysical).

The role of (spiral) waves in transporting angular momentum, and thus influencing radial structure is not clear, and will not be considered here.

B. Local Gravitational Stability (Toomre Q)

Larson (1988) and Kennicutt (1989) have recently summarized the theoretical indications and observational evidence, respectively, showing that Toomre's (1964) gravitational stability parameter Q = $c\kappa/\pi G\Sigma$ is of order unity throughout the star-forming part of a galaxy disk. In the isothermal, v_θ = constant part of a disk this also implies $\Sigma \propto 1/r$, consistent with the other constraints, but also setting the value of Σ.

C. Secular Kinetic Equilibrium

Large clouds may have long mean free paths ($\lambda \approx 1$ kpc.) in galaxy disks, so kinetic (random walk) effects must be considered. Diffusive mass fluxes between adjacent annuli of width λ must balance, so Σ r c = constant. (For practical purposes this is equivalent to zero self-diffusion.) Momentum Flux balance between adjacent annuli implies, Σ r c v_θ = constant. This condition is not equivalent to minimizing hydrodynamic viscous shear. E. g. the latter is zero when $v_\theta \propto r$, and $\Sigma \propto 1/r$, but the present condition is not satisfied!

III. Conclusions

- Both the available data and theoretical considerations suggest that the unique equilibrium surface density profile in the flat-rotation-curve region of the disk is $\Sigma \propto 1/r$. If this profile is also stable to non-axisymmetric disturbances, then this region may be regarded as a gas reservoir for the galaxy.
- The existence of equilibrium or quasi-steady profiles in the inner disk, where v_θ increases with r is more problematic. If $v_\theta \propto r$ in this region, then there are two hydrodynamic equilibrium forms: $\Sigma \propto 1/r$ or Σ = constant. There are examples of both forms in the observations. However, neither is a kinetic equilibrium form, so we can expect diffusive processes to funnel material from the reservoir region inwards. At the same time, the critical density for local gravitational instability is constant in regions where $v_\theta \propto r$, so if $\Sigma \approx \Sigma_{crit}$, star formation processes may oppose the kinetic ones. We do not yet understand the outcome of this interplay of forces.

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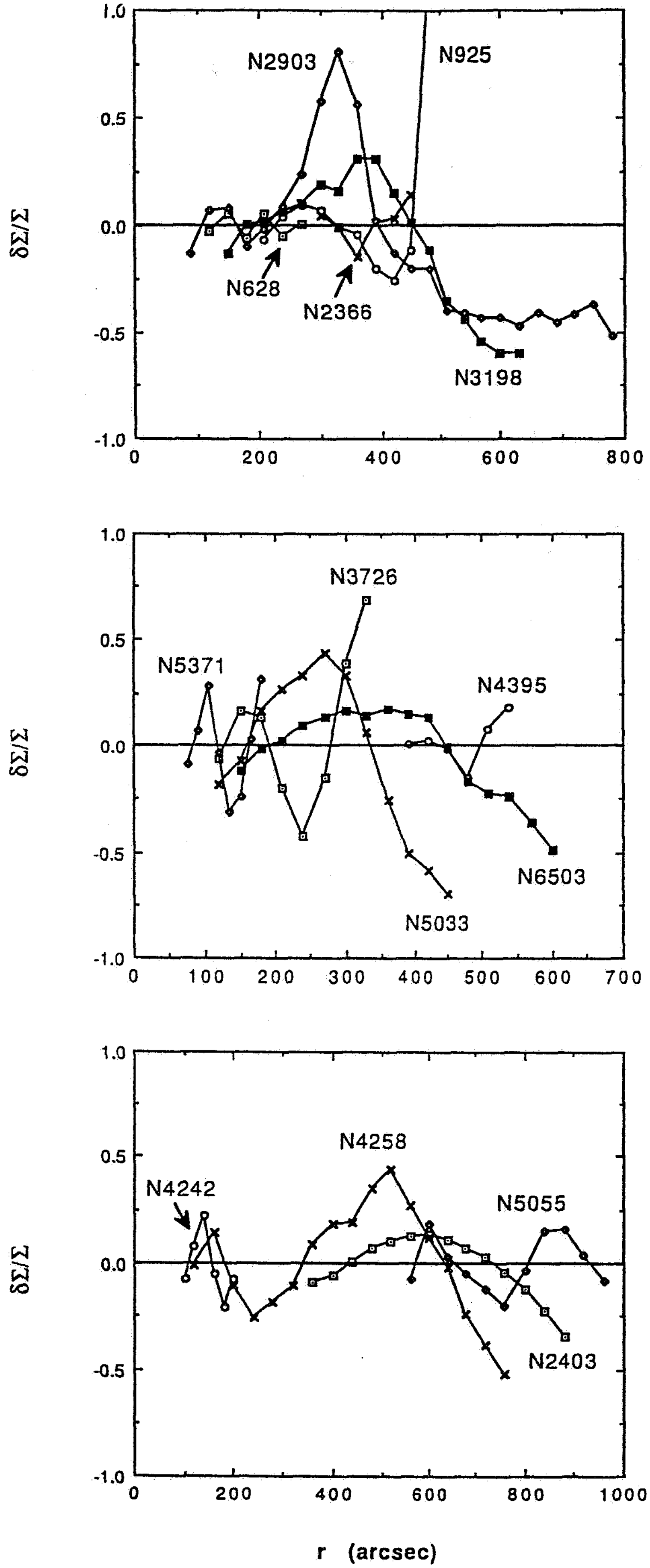

Figure 1a-c. Shows the deviation of the azimuthally averaged gas surface density profiles from a best-fit 1/r profile using the data from Wevers (1984) as described in the text.