VERTICAL MOTION AND THE THICKNESS OF HI DISKS: IMPLICATIONS FOR GALACTIC MASS MODELS

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1. INTRODUCTION

Most studies of the mass distribution in spiral galaxies have been based on the observed rotation curves. A serious ambiguity in this approach has always been that the rotation curve contains in itself no information on the mass distribution in the direction perpendicular to the galactic plane. The usual assumption has been that the mass in late type galaxies is distributed as the light, namely outside the central bulge in a highly flattened disk. In recent years it has been found that the rotation curves decline little or not at all, indicating large increases in the local value of M/L with increasing galactocentric radius (e.g. Bosma and van der Kruit, 1979). On the basis of dynamical arguments involving stability it has been suspected that the material giving rise to the large values of M/L - the "dark matter" - is distributed in the halos of these galaxies, so that the assumption of a flat mass distribution would have to be wrong.

This question can be elucidated by an independent measurement of the mass distribution near the plane of the disk. One does this by comparing the z-distribution of a disk component with its vertical velocity dispersion $\langle V_z^2\rangle^{\frac{1}{2}}$. A component that is observationally accessible in external galaxies is the neutral hydrogen.

Assume that the total mass distribution in a galactic disk can be approximated by that of a locally isothermal sheet:

$$\rho(R,z) = \rho(R,o)\ \mathrm{sech}^2(z/z_o)\ , \qquad (1)$$

which corresponds to a surface density $\sigma(R) = 2z_o\rho(R,o)$. The velocity dispersion $\langle V_z^2\rangle^{\frac{1}{2}}$ corresponding to this mass distribution is

$$\langle V_z^2\rangle^{\frac{1}{2}} = \left[\pi\, G\sigma(R) z_o\right]^{\frac{1}{2}} \qquad (2)$$

and the force field in the z-direction is

E. Athanassoula (ed.), Internal Kinematics and Dynamics of Galaxies, 69–76.

$$K_z = -2\pi G\sigma(R) \tanh (z/z_o) . \qquad (3)$$

In a series of papers on surface photometry of edge-on spiral galaxies, van der Kruit and Searle (1981a, b; 1982a, b; hereafter KSI-IV) have shown that the light distribution of the old disk population in spiral galaxies has the distribution of (1) with z_o independent of R and luminosity density L(o,R) = L(o,o) exp (-R/h) out to a relatively sharp edge at $R_{max} \approx 4$-5 h. In the appendix to KSIII they showed that (3) is indeed a reasonable approximation to K_z for $z \lesssim z_o$ when the mass is distributed as the light in this model: i.e. $\rho(R,z) = (M/L)\ L(R,z)$.

A second isothermal component with velocity dispersion $\langle V_z^2\rangle^{\frac{1}{2}}_{II}$ that does not add significantly to the total force field will be distributed in the field (3) as

$$\rho_{II}(R,z) = \rho_{II}(R,o) \ \mathrm{sech}^{2p} \ (z/z_o) \qquad (4)$$

with $p = \langle V_z^2\rangle / \langle V_z^2\rangle_{II}$. For the case of HI we have $p \gtrsim 1$; the FWHM of the HI-layer can then be approximated by (see van der Kruit, 1981)

$$(z_{\frac{1}{2}})_g \sim 1.7 \ \langle V_z^2\rangle^{\frac{1}{2}}_g \ [\pi G\sigma(R)/z_o]^{-\frac{1}{2}} , \qquad (5)$$

where $\langle V_z^2\rangle^{\frac{1}{2}}_g$ is the velocity dispersion of the HI gas.

The most recent work regarding the vertical HI distribution in our own Galaxy is that of Celnick et al. (1979) who also give references to earlier work. Their conclusions can be summarized as follows: (1) The z-distribution of HI can be understood as the equilibrium distribution of an isothermal gas in the Galactic force field. (2) A model with a mixture of two isothermal gas distributions each with its own velocity dispersion is not supported by the data. (3) The derived HI parameters can be made consistent with other dynamical constraints if a considerable fraction of the Galactic mass is distributed outside the disk.

We can test equation (5) for the solar neighbourhood. Oort's (1965) curve for K_z can be fitted to (3) with z_o = 0.6-0.7 kpc and $\sigma(R_o)$ = 80-100 $M_\odot$ pc^{-2} (see KSI and KSIII). Stars of spectral type later than early G show a z-distribution corresponding to a z_o of 0.6-0.8 kpc in the solar neighbourhood (see also KSI). From the data in Jackson and Kellman (1974) and their own, Celnick et al. imply local values of $(z_{\frac{1}{2}})_g$ around 300 pc with an uncertainty of about 25%. The expected values for $\langle V_z^2\rangle^{\frac{1}{2}}_g$ from (5) then are 7-9 km s^{-1}. HI observations in our Galaxy and in external galaxies summarized by Baldwin (1981), van der Kruit (1981) and below suggest that values in the range 7-10 km s^{-1} are typical for the velocity dispersion in the HI gas in galactic disks. Evidently eq. (5) applies to the solar neighbourhood, and can be expected to be also applicable to external galaxies. The result also suggests that magnetic fields and cosmic ray pressure play no important role in establishing the z-distribution of the HI.

2. HI OBSERVATIONS OF FACE-ON GALAXIES

The determination of the velocity dispersion in the gas is only possible in those systems that show only a small gradient in their line-of-sight velocity field across the beam of the radio telescope. Clearly the safest approach is to observe spirals that are very close to face-on with a synthesis instrument. We have selected three such galaxies on the basis of the small width of their integrated HI profiles to observe with the Westerbork synthesis radio telescope, and these three systems are now briefly discussed in turn.

NGC 3938 (van der Kruit and Shostak, 1982) is an ScI with an optical radius determined from our surface photometry of about 3 arcmin. The velocity field is consistent with pure rotation and the corresponding rotation curve is constant from within 1' out to 4' at a velocity of about 38 km s^{-1} in the line-of-sight. Profiles are always fitted well by Gaussians and the median velocity dispersion in rings of constant galactocentric radius is 10±1 km s^{-1} at all radii. For a discussion of the reduction techniques we refer to our paper.

NGC 628 (M 74) (in preparation) is also an ScI, and our deep surface photometry traces the galaxy out to about 5 arcmin radius. At 21 cm we detect HI out to at least 13 arcmin and Briggs (1982) has found HI-emission out to 20 arcmin at Arecibo. Beyond the optical radius the velocity field indicates that the HI layer is warped with respect to the inner plane, but the area within the optical boundary has a well organized velocity field that is to within an r.m.s. residual of 3 km s^{-1} consistent with pure rotation. The rotation velocity in the line-of-sight is about 25 km s^{-1} over this area at all radii larger than 1'. The HI distribution follows the optical spiral structure and in these arms the 21-cm emission is so strong that our profiles have peaks in excess of 10 times the r.m.s. noise in our channel maps. Even at this high S/N Gaussians provide excellent fits to the profiles and we find no evidence for extended wings corresponding to a significant second component with a higher velocity dispersion.

The ring averaged velocity dispersion has a median value of about 9-10 km s^{-1} in the central area declining to about 7 km s^{-1} at the optical boundary and remains at this level to the edge of the observed HI distribution. Over the optical extent we find that in the arms the mean dispersion is about 10 km s^{-1} compared to about 7 km s^{-1} in the interarm regions. The radial decline probably reflects the fact that further from the centre a larger fraction of the solid angle of a ring is occupied by interarm regions. The higher velocity dispersion in the arms may result from recent energy input from stellar winds and supernovae in regions of vigorous star formation. In NGC 3938 we do not separate arm and interarm regions and if most HI is concentrated in arms, the arm emission will dominate the emission from any one beam area. This may explain the observed constancy of the velocity dispersion in that galaxy.

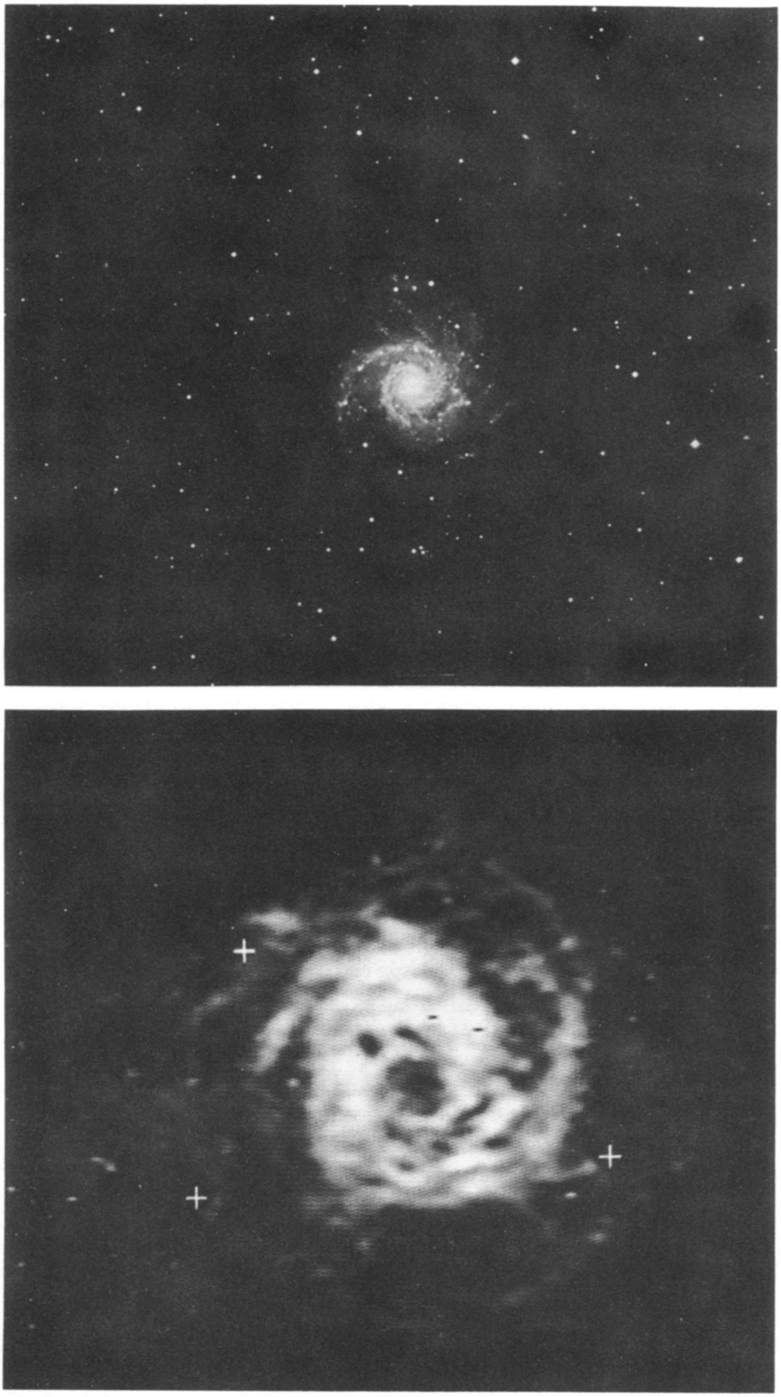

Figure 1 Optical and HI distributions in the spiral galaxy NGC 628. The two sharp dark features in the HI map are a processing artifact. Both distributions are shown to the same scale.

NGC 1058 (in preparation) is an ScII-III galaxy and has the narrowest integrated HI profile known to us. Our integrated Westerbork profile is fitted very accurately with a Gaussian of dispersion 11.1 km s^{-1}. In spite of the fact that Boroson (1981) traced the galaxy optically out to only 2' radius we find HI out to almost 7 arcmin. Again we find beyond the optical radius evidence from the velocity field of a warped HI layer. The inner velocity field is consistent to within a 4 km s^{-1} r.m.s. residual with pure rotation. The rotation velocity in the line-of-sight is about 12 km s^{-1}.

The median velocity dispersion is 7-8 km s^{-1} at all radii. The HI distribution shows distinct spiral structure out to the maximum extent of the gas, but the velocity dispersions in the arms and the interarm regions are indistinguishable. Since NGC 1058 shows less evidence for vigorous star formation and most of this spiral structure occurs beyond the optical extent this is not in contradiction to our result on NGC 628.

In view of the results presented we conclude that: (1) There is no evidence for patterns of systematic z-motions across the optical extents of the disks. (2) There is no evidence for two distinct gas components with different velocity dispersions. (3) The HI in galactic disks has velocity dispersions in the range 7-10 km s^{-1}, where the higher values may correspond to areas of vigorous star formation.

3. THE MASS DISTRIBUTION IN SPIRAL GALAXIES

The edge-on spiral galaxy NGC 891 can be used to apply the method described in the Introduction. Sancisi and Allen (1979) have measured the HI distribution, while in KSII the light distribution of the old disk population has been derived. Van der Kruit (1981) showed from this that the observations of Sancisi and Allen can be represented very well by a model in which M/L is constant throughout the disk, while a model in which all the mass indicated by the rotation curve is concentrated in the disk is in disagreement with these data. The best fitting model had $(z_{\frac{1}{2}})_g = 0.22 \exp (R/2h)$ kpc with h = 4.9 kpc at the assumed distance of 9.5 Mpc (model I in table 1 of van der Kruit, 1981). The distribution of light from the old disk population with the revised luminosity scale of KSIII has $L(o,R) = 2.4 \times 10^{-2} \exp (-R/h)\ L_{\odot,J}\ pc^{-3}$. Using (5) with $\sigma(R) = 2z_o\rho(o,R)$ and $z_o = 0.99$ kpc this gives $(M/L)_{old\ disk} = 9.2 \times 10^{-2} \langle V_z^2 \rangle_g^{\frac{1}{2}}$. Our range above for $\langle V_z^2 \rangle_g^{\frac{1}{2}}$ of 7-10 km s^{-1} then implies $(M/L)_{old\ disk} = 4.5\text{-}9\ M_{\odot}/L_{\odot,J}$. In the solar neighbourhood the old disk population contributes about half of the total surface brightness of the disk, so that M/L for the entire disk population would be expected to be a factor two or so lower.

The constancy of $(M/L)_{old\ disk}$ implies that the dark matter resides in the halo. For a value of 7 for $(M/L)_{old\ disk}$ it follows that of the total mass within the optical radius of NGC 891 only about one-third

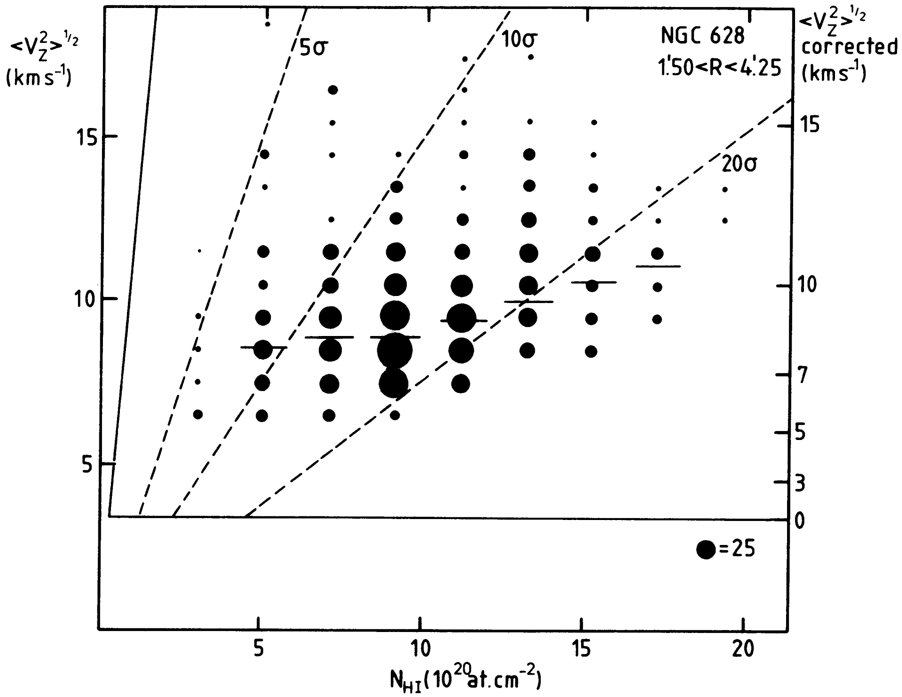

Figure 2

The rms z-velocity dispersion as a function of HI surface density over the optical extent of NGC 628. Area of circles is proportional to the number of pixels having the given values. Note the increase in the median value of $<v_z>^{\frac{1}{2}}$ (indicated by horizontal lines) with increasing surface brightness. Dotted lines give signal-to-noise values.

is found in the disk. Van der Kruit and Searle use photometry of 6 other edge-on galaxies and estimated parameters for our Galaxy to show that in general $(M/L)_{\text{old disk}} \approx 7$ implies that only one-third to half of the total mass within the optical radius resides in the disks (see KSIII).

With the mass distribution obtained above for NGC 891 we can make some estimates of properties relevant to our assumptions. At 10 kpc from the centre for example we find that the mass density at z = 0 for the disk exceeds that of the (spherical) halo by a factor of about 4, while this ratio drops to about 2 at the edge of the disk at 21 kpc. This confirms that the disk can in first approximation be described as self-gravitating over all of its radial extent. Everywhere the surface density of HI is much smaller than that of the disk. At R_{max} the modelling shows that of the total surface density of the disk 10-20% is in the form of HI so that the assumption necessary for eq. (4) also is confirmed.

In KSIV a study is made of the edge-on Sab galaxy NGC 7814 whose light distribution is dominated by that of the spheroid. They estimate that the disk contains only 2-3% of the total mass within the optical radius of 22 kpc, so that the rotation curve can be used directly to infer the local M/L in the bulge/halo. It is then found to increase from about 15 in the inner regions to about 160 at 22 kpc. If the dark matter is in the form of faint stars of low mass and black dwarfs that formed along with the luminous stars in the spheroid, the local M/L and the mean stellar metal abundance should be inversely proportional. The colour gradient in the spheroid of NGC 7814 is consistent with this (see KSIV for a more detailed discussion).

Our final conclusion, then, is that the halos of spiral galaxies contain more than half the mass within the optical boundaries. The local M/L values in the halos go up to at least 10^2 at these maximum galactocentric distances, but are close to constant throughout the disks.

REFERENCES

Baldwin, J.E. 1980, The Structure and Evolution of Normal Galaxies (ed. D. Lynden-Bell and S.M. Fall), Cambridge Univ. Press, p. 137.

Boroson, T. 1981, Ap. J. Suppl. 46, 177.

Bosma, A., Kruit, P.C. van der 1979, Astron. Astrophys. 79, 281.

Briggs, F.H. 1982, preprint.

Celnick, W., Rohlfs, K. Braunsfurth, E. 1979, Astron. Astrophys. 76, 24.

Jackson, P.D., Kellman, S.A. 1974, Ap. J. 190, 53.

Kruit, P.C. van der 1981, Astron. Astrophys. 99, 298.

Kruit, P.C. van der, Searle, L. 1981a, Astron. Astrophys. 95, 105 (KSI).

Kruit, P.C. van der, Searle, L. 1981b, Astron. Astrophys. 95, 116 (KSII)

Kruit, P.C. van der, Searle, L. 1982a, Astron. Astrophys. 110, 61 (KSIII).

Kruit, P.C. van der, Searle, L. 1982b, Astron. Astrophys. 110, 79 (KSIV).

Kruit, P.C. van der, Shostak, G.S. 1982 Astron. Astrophys. 105, 359.

Oort, J.H. 1965, Stars and Stellar Systems V: Galactic Structure (ed. A. Blaauw and M. Schmidt), Univ. of Chicago Press, p. 455.

Sancisi, R., Allen, R.J. 1979, Astron. Astrophys. 74, 73.

DISCUSSION

WHITE : The inverse relation between M/L ratio and metallicity which you suggest, requires each radial shell of stars to evolve like a "closed box" enrichment model over several stellar generations. Such a requirement puts some constraints on the formation of your systems, and suggests that they may have collapsed slowly like LARSON's early models for elliptical galaxies.

VAN DER KRUIT : One can infer from the absence of populations intermediate between disk and spheroid in NGC7814,that the abundance gradient in the spheroid (and on the hypothesis above also the M/L gradient) existed before virialisation and collapse (see Van der Kruit and Searl, Astron Astrophys 110, 79). If so, the abundance and M/L are correlated with binding energy in the protogalaxy and this correlation can be expected to survive the collapse and violent relaxation (see Van Albada, 1982, Mon. Not. R. Astr. Soc., in press).

DRESSLER : You found a local M/L of ∿ 160 for the outermost point in NGC7814. What is the global M/L implied within that radius, i.e. how much has the global M/L risen from the center in your model ?

VAN DER KRUIT : Our plates are over-exposed in the central region so that we have difficulty estimating the total light of the galaxy. Reasonable extrapolations of the radial light profile to the center give integrated M/L out to 22 kpc of the order of 10 $M_\odot/L_\odot$.

WIELEN : I would like to draw attention to a paper by B. FUCHS and myself on the results of the workshop on "The Milky Way", held in Vancouver in May 1982 (Astrophysics and Space Science Library, Vol. 100, D. Reidel Publishing Company). In this paper we also discuss the thickness of stellar disks in which orbital diffusion operates.