HI velocity dispersions and flaring: Disk masses and the shape of dark matter halos

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Abstract.
I briefly review the use of measurements of the HI velocity dispersion and gas layer flaring in galaxy disks to determine the baryonic mass of the disks. I compare that to results from stellar dynamics. In systems with low-mass disks, flaring can also provide information on the flattening of the dark matter halos. New results from the thesis of Jess O'Brien are summarized, in particular an application to UGC 7321 that shows the dark matter halo in that galaxy to be close to spherical.

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HI layers and disk masses

The thickness of the gas layer in a disk galaxy can be used to measure the surface density of the disk. Assume the density distribution of the exponential, locally isothermal disk of van der Kruit & Searle [13]:

$$\rho_*(R,z) = \rho_*(0,0)\exp(-R/h)\,\mathrm{sech}^2(z/z_\circ).$$

If the HI velocity dispersion $\langle V_z^2\rangle_{\rm HI}^{1/2}$ is independent of radius (as e.g. in the face-on spiral NGC 628, see Shostak & van der Kruit [9]) *and* isotropic, and if the stars dominate the gravitational field, the HI layer has a full width at half maximum (to $\lesssim 3\%$) of

$$W_{\rm HI} = 1.7\langle V_z^2\rangle_{\rm HI}^{1/2}\left[\frac{\pi G(M/L)\mu_\circ}{z_\circ}\right]^{-1/2}\exp(R/2h).$$

So the HI layer increases exponentially in thickness with an e-folding $2h$. This has first been derived and applied to HI observations of NGC 891 by van der Kruit [10]. One has to be careful to distinguish signatures for flaring from those of residual inclination away from exactly edge-on. Such studies can determine whether galaxies have in general *maximum disks* or not. According to Sackett [7], in maximum disk fits it is found that the ratio of the maximum of the rotation curve of the disk alone ($V_{\rm rot,disk}$) to the observed maximum rotation is,

$$\frac{V_{\rm rot,disk}}{V_{\rm rot,obs}} = 0.85 \pm 0.10. \qquad (1)$$

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The modelling, using photometry from van der Kruit & Searle [14], indicated that $V_{\rm rot,disk}$ of NGC 891 is ~ 140 km/s. The observed value is 225 ± 10 km/s, so the ratio in eqn.(1) is ~ 0.6, and NGC 891 is clearly sub-maximal.

In other systems similar results were found; e.g. in NGC 4244 Olling [5] deduced from the flaring a disk-alone rotation of 40 to 80% of that of observed rotation.[2] For our Galaxy my preferred values are $V_{\rm rot,disk} \sim 155 \pm 30$ and $V_{\rm rot,obs} \sim 225 \pm 10$ km/s, so that the ratio is 0.69 ± 0.14 and the Milky Way also is sub-maximal.

It is important to note that all determinations of the property $V_{\rm rot,disk}/V_{\rm rot,obs}$ in eqn.(1) from both HI flaring and those from stellar dynamics, have been consistent. This similarity of completely independent determinations is remarkable and encouraging. Here are values for $V_{\rm rot,disk}/V_{\rm rot,obs}$ from three independent studies using stellar dynamics[3], which can be compared to the HI flaring results above.

van der Kruit & Freeman [12]	0.6 ± 0.2
Bottema [1]	0.63 ± 0.15
Kregel, van der Kruit & Freeman [3]	0.58 ± 0.18

The conclusion is that all spirals are sub-maximal, except possibly some of the largest and brightest ones (see Kregel, van der Kruit & Freeman [3] and van der Kruit [11]).

The flattening of dark matter halos

The flaring of the HI layer can be used in principle to measure the flattening of the dark matter halo. This approach has been taken in a recent Ph.D. thesis at ANU by Jess O'Brien. This study has been submitted as a series of four papers[4]. The procedure is to determine the force field of the halo in the *vertical* direction using HI-layer flaring and in the *radial* direction from rotation curve decomposition, and then comparing the two to measure the shape of the dark matter halo. This is optimised by selecting small, HI-rich, late-type edge-on galaxies which are known to often have *low-mass disks* such that the rotation curve is predominantly determined by the dark matter.

Existing methods to model the (x,V)-diagram have been extended to include at the same time the HI velocity dispersion in addition to the HI surface density and the rotation curve, all as a function of galactocentric radius. This 'radial decomposition XV modelling method' was extensively tested and applied to HI-data of a sample of 8 HI-rich, late-type edge-on galaxies (from ATCA or VLA archive).

The radial distributions of the HI velocity dispersions show significant structure. These and the warping profiles display usually fairly good symmetry.

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[2] Actually, the flaring of the HI-layer in NGC 4244 was used by Olling [4] to infer that the dark matter is highly flattened (but see Olling & Merrifield [6], who found for the Galaxy halo closer to spherical).

[3] Note that van der Kruit & Freeman [12] used the property Y defined as a criterion for global stabiility by Efstathiou, Lake & Negroponte [2]: $Y = V_{\rm rot}\sqrt{h/GM_{\rm disk}} \gtrsim 1.1$ for stability. This is –up to a factor 0.62 for an infinitessimally thin exponential disk– the reciprocal of the ratio in eqn.(1); van der Kruit & Freeman [12] found $Y = 1.0 \pm 0.3$.

[4] Paper I: J.C. O'Brien, K.C. Freeman, P.C. van der Kruit & A. Bosma, A.&A. submitted (2009); Papers II-IV: J.C. O'Brien, K.C. Freeman & P.C. van der Kruit, A.&A. submitted (2009)

UGC 7321

There is a detailed application to UGC 7321 in paper IV of the O'Brien et al. series. HI-data are from the VLA archive (observations of Lyn Matthews) and the optical (*R*-band) photometry has been provided by Michael Pohlen (from SDSS). There is a well-defined, highly symmetric flaring profile of the HI-layer. The symmetry holds also for the rotation curve, the velocity dispersion profile and the HI surface density distribution. For the optical datea the observed surface brightness distribution is used to infer the deprojected radial and vertical luminosity space density profiles.

The dark halo forces are modelled using the flattened pseudo-isothermal halo from Sackett et al. [8], which has a spatial density distribution

$$\rho(R,z) = \frac{\rho_{\mathrm{h},\circ} R_{\mathrm{c}}^2}{R_{\mathrm{c}}^2 + R^2 + z^2/q^2}.$$

The resulting shape of the rotation curve (at $z = 0$) is independent of the flattening $q = c/a$. The best fit decomposition of the rotation curve then has a disk M/L_R of 1.05. This is far from maximum disk and the disk forcefield is small w.r.t. to that of the halo. Note that this M/L_R is not constrained by the flaring of the HI layer and could be smaller!

The gradient of the vertical force $\partial K_{\mathrm{z}}/\partial z$ as a function of R, deduced from the flaring and HI velocity dispersion at those radii using hydrostatic equilibrium is

$$\frac{\partial K_{\mathrm{z}}(R,z)}{\partial z} = \frac{\partial^2}{\partial z^2}\left[\sigma_{\mathrm{g}}^2(R)\ln\rho_{\mathrm{g}}(R,z)\right].$$

For Gaussian gas density distributions and velocity dispersion σ_{g} this gives

$$\frac{\partial K_{\mathrm{z,tot}}(R,z)}{\partial z} = \frac{\sigma_{\mathrm{g}}^2(R)}{(\mathrm{W_{HI}}(R)/2.355)^2}$$

and is constant in z. We need to derive this force gradient for the stars and the gas and these can be determined using Poisson's equation

$$\frac{\partial K_{\mathrm{z,i}}(R,z)}{\partial z} = -4\pi G\rho_{\mathrm{i}}(R,z) + \frac{1}{R}\frac{\partial(RK_{\mathrm{R,i}})}{\partial R} = -4\pi G\rho_{\mathrm{i}}(R,z) + \frac{1}{R}\frac{\partial V_{\mathrm{rot,i}}^2(R)}{\partial R}.$$

Then we determine the gradient due to the dark matter halo from

$$\frac{\partial K_{\mathrm{z,halo}}(R,z)}{\partial z} = \frac{\partial K_{\mathrm{z,tot}}(R,z)}{\partial z} - \frac{\partial K_{\mathrm{z,stars}}(R,z)}{\partial z} - \frac{\partial K_{\mathrm{z,gas}}(R,z)}{\partial z}$$

and fit this to the equations for the flattened pseudo-isothermal halo.

We first find that the disk M/L_R of 1.05 is too high to provide a physical solution. Models were then fit with three free parameters: the asymptotic rotation speed of the halo, the stellar M/L_R and the flattening q. The core radius of the halo was kept fixed to that from the rotation curve analysis. With least-squares minimisation this produced a best shape of $q = 1.0 \pm 0.1$, independent of the other parameters. So, the dark halo is very close to spherical. The best fit actually occurs for $M/L_R = 0$, but $M/L_R = 0.2$ is almost as good and is illustrated in Figure 1. The actual fits were done over the range R = 3 to 7 kpc, but were successful over R = 2 to 9 kpc.

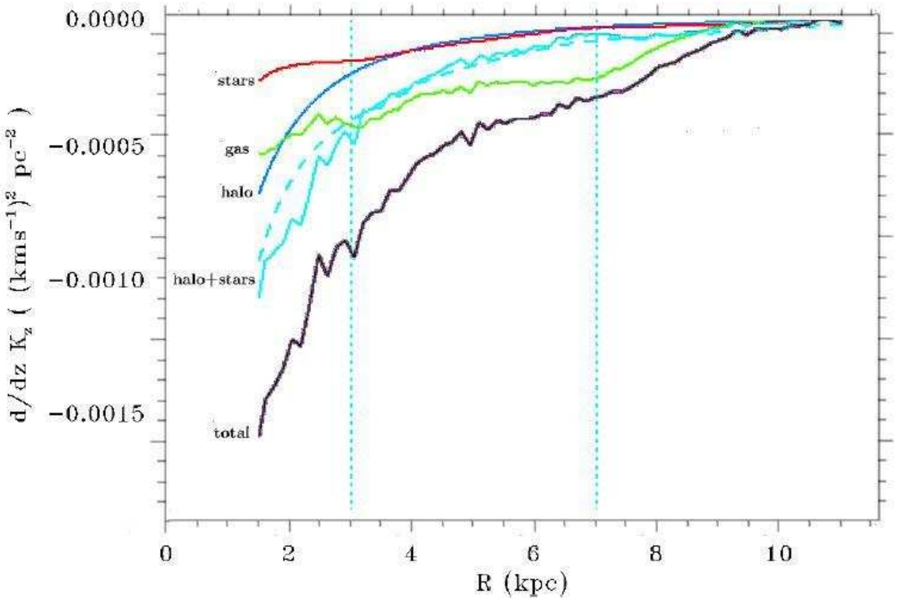

FIGURE 1. The gradients in the vertical force field for various components in UGC7321. The curve 'halo+stras' is derived from the curve 'total' (determined from the HI flaring) minus the contribution from the gas. The dashed line shows the fit to this line. The disk M/L_R is 0.2 and this provides the curve labelled 'stars'.

Conclusions

- Spiral disks are sub-maximal, except possibly for large, massive spirals.
- In UGC 7321 the dark matter halo seems to be almost spherical.

Other galaxies in O'Brien's sample remain to be analysed. Important remaining questions are whether or not the HI velocity dispersion is indeed isotropic, as has been assumed, and how the HI velocity dispersion varies with height above the plane.

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