The shape of the dark matter halo of NGC 4244

Rob P. Olling, J. H. van Gorkom
Columbia University
538 West 120^{th} street box 42, New York, NY10027
olling@tosca.phys.columbia.edu

ABSTRACT

We present a preliminary analysis of the flaring behavior of the hydrogen layer of the nearby almost edge-on ($i \approx 85^o$) Sc galaxy NGC 4244 (Fig. 1). We developed a new technique to determine the inclination and the thickness of the gas layer from many channels simultaneously. Furthermore we show that this method is not limited to edge-on galaxies only. Each side of the galaxy has been analyzed separately. Comparing the measured thickness of the hydrogen layer with model predictions we conclude that the galaxy mass model which reproduces the measured widths best is composed of a stellar disk which is about one-third as massive as maximum-disk and a DM-halo with $q = 0.5 + / - 0.3$.

1. Introduction

Little is known about the shape of dark halos : the equatorial rotation curve is a one dimensional probe only. Both spherical and flat dark matter (DM) halo models can reproduce the same observed rotation curve. The polar ring galaxy NGC 4650A has a dark halo as flattened as E6-E7 (Sackett & Sparke, 1990 and Sackett *et al.*1994a). Recently, Sackett *et al.*(1994b) reported the discovery of a flattened ($q = c/a \approx 0.5$) *luminous* halo (possibly of dynamical significance) around NGC 5907.

Like the polar rotation curve, the thickness of the gas layer depends on the shape of the DM-halo (Olling and van Gorkom 1992, OvG92; Maloney 1993, M93; Kundić, Hernquist and Gunn 1993, KHG93). In this poster we present the first results of a new method (proposed by Olling 1995, O95) to determine the flattening of DM-halos from high resolution HI measurements.

2. Some theory

Flatter DM-halos have larger midplane densities (M93, O95), so that gas layers immersed in such a flat halo will be comparatively thin. For the analysis of NGC 4244 we follow the approach taken by O95 and determine the vertical distribution of the gas from the global potential of the galaxy. The global mass distribution is composed of an exponential stellar disk and a flattened isothermal DM-halo. For this global mass distribution we calculate the global potential. If the gas is isothermal in z, then we can use the equation of hydrostatic equilibrium

$$\sigma_z(R)^2 \frac{d\ (\rho_{gas}(z))}{d\ z} = \rho_{gas}(z)\ K_z(z)\ =\ -\rho_{gas}(z)\ \frac{d\ \Phi(R,z)}{d\ z}, \qquad (1)$$

from which the (zeroth-order) density distribution of the gas follows :

$$\rho_{gas}(R,z) = \rho_{gas}(R,0) \exp\left(-\Phi(R,z)/\sigma_z(R)^2\right)\ . \qquad (2)$$

Equation (2) can be used to calculate an approximation to the potential due to the self-gravity of the gas :

$$\Phi_{GAS}^{approx}(R,z) = -2\pi G \int_0^z dz' \Sigma_{GAS}(R,z') \ . \tag{3}$$

The next order approximation to $\rho_{gas}(R,z)$ is calculated from equation (2), where we take Φ to be $(\Phi_{GAS}^{approx} + \Phi_{STARS} + \Phi_{HALO})$. To the resulting distribution we fit a Gaussian to determine its Full Width at Half Maximum (FWHM$_z$). Beyond the optical disk the thickness of the gas layer increases approximately linearly (OvG92; M93; KHG93; O95) with radius :

$$\mathrm{FWHM}_z \approx 2.35 \left(\frac{\sigma_z}{V_{rot,max}} \right) \ R \ (\mathrm{kpc}), \tag{4}$$

where $V_{rot,max}$ is the peak rotation velocity.

3. The gaseous disk of NGC 4244

High resolution (175 pc x 5 km/s) VLA (B-, C-, and D-array) HI observations were obtained for NGC 4244. The rotation curve was measured from major axis-velocity plots. Several different disk-halo decompositions are shown in Figure 2., both maximum-disk and one-third-maximum-disk models fit the observed rotation curve equally well.

3.1. Determining the thickness of the gas layer

For a perfectly edge-on galaxy the width of the gas layer at a given galactocentric radius,R, is measured in that channel which has a velocity difference w.r.t. the systemic velocity equal to the rotation speed at that radius.

If the galaxy is not exactly edge-on, the relation between the measured widths and the intrinsic gas layer thickness ,FWHM$_z(R)$, is less simple. Consider for example a galaxy with a uniform surface density, a flat rotation curve, and zero gaseous velocity dispersion ($\sigma_z(R){=}0$). If observed with square channels (ΔV_{chan}), any channel will be sensitive to gas in a wedge centered around $\theta = \arccos\left(V_{chan}/(V_{rot}\sin i)\right)$, while the opening angle of the wedge is given by:

$$\Delta\theta = \arccos\left\{ \frac{(V_{obs} - 0.5\Delta V_{chan})}{V_{rot}(R)\ \sin(i)} \right\} - \arccos\left\{ \frac{(V_{obs} + 0.5\Delta V_{chan})}{V_{rot}(R)\ \sin(i)} \right\} . \tag{5}$$

For almost edge-on systems the two wedges (the near and far side respectively) will be superimposed. At lower inclinations, the wedges bifurcate, and we observe the classical "butterfly" shape. The projected width on the sky is thus a combination of the projected gas layer thickness (FWHM$_z \times \sin(i)$) and the projected "wedge" width* (FWHM$_w \times \cos(i)$). As both the vertical and the planar distributions are Gaussian, the projection on the sky will also be Gaussian. The observable width (FWHM$_O$) is given by :

$$\mathrm{FWHM}_O^2 \approx \mathrm{FWHM}_B^2 + (\mathrm{FWHM}_z \sin i)^2 + \left(\mathrm{FWHM}_w^2 + (2.35\ P_w)^2\right) \cos^2 i \ , \tag{6}$$

where FWHM$_B$ is the beam size. When the inclination is so low that the near and far sides are clearly separated, the P_w-term has to be dropped. As we have

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* For real galaxies, the wedge-width is affected by the rotation curve, the velocity dispersion and the surface density distribution. Once these parameters are measured, the exact shape of the "wedge" can be calculated for all radii. Model calculations indicate that, at any major axis distance, these "wedges" can be well approximated by two Gaussian of width FWHM$_w$ centered at $\pm P_w$.

measurements of FWHM_O, and are able to calculate FWHM_w and P_w, for many (≥ 10) channels, we can solve (6) for inclination and FWHM_z in a least squares sense. We applied this technique to simulated HI-observations of a galaxy like NGC 4244 at inclinations of $85^o, 72^o, 63^o$ and 55^o : the input values for FWHM_z and i are recovered very well for all but the lowest inclination.

Since each spectral line channel samples a small range of azimuth only, we can determine the thickness of the gas layer for non edge-on systems as well. From calculations at different gaseous velocity dispersion we find that the width (of a typical channel), as projected on the sky, of the "wedge" can be approximated as : $\mathrm{FWHM}_w \approx 4\,\{MAX(\sigma_z, \Delta V_{chan})/(V_{rot}\sin(i))\}\;R\cos(i)$. As the projected width of an isothermal gas layer in the potential of a DM-halo increases linearly with radius (eqn. [4] $\times \cos(i)$) as well, we find that the ratio of the vertical and planar projected widths depends on inclination only : $\{\mathrm{FWHM}_z(R)/\mathrm{FWHM}_w(R)\} \approx 0.57\sin(i)\tan(i)$. In order to reliably determine the thickness of the gas layer its width projected on the sky needs to be larger than, the other contributors to the apparent width (beam size and FWHM_w). Thus we find a lower limit to the inclination of about 63^o : similar to inclination cutoff observed in our numerical experiments.

4. Conclusions

For NGC 4244, we present the results in Fig. 3. Both sides, as well as the average are indicated. High (10") and low (38") resolution data are presented. A small warp (lower panel) and a flaring gas layer (upper panel) can be seen, notice the similarity of the two sides. For the comparison with the model predictions we fixed the inclination to 85^o so that the widths beyond 10 kpc are upper limits. In Figure 4 we show these widths superimposed on model predictions. The radial coordinate is normalized by the optical scale-length (h_R). The numbers on the right side of the box indicate the corresponding halo flattenings. Inside the optical disk ($R \leq 5h_R$), the measurements clearly require a low $\mathcal{M}/\mathcal{L}$ stellar disk. For the "maximum-disk" value ($\mathcal{M}/\mathcal{L}$ =5.10) the observed widths are much larger than the model predictions. For the preliminary analysis presented in this paper the lowest $\mathcal{M}/\mathcal{L}$ -value (1.57, or about 1/3-maximum-disk) agrees better. As the measurements do not extend very far beyond the optical disk, the DM-halo flattening can not be determined with great accuracy. For q-values in the range 0.2-0.8, the predictions are consistent with the observations.

ACKNOWLEDGEMENTS

This work was supported in part through an NFS grant (AST-90-23254) to Columbia University.

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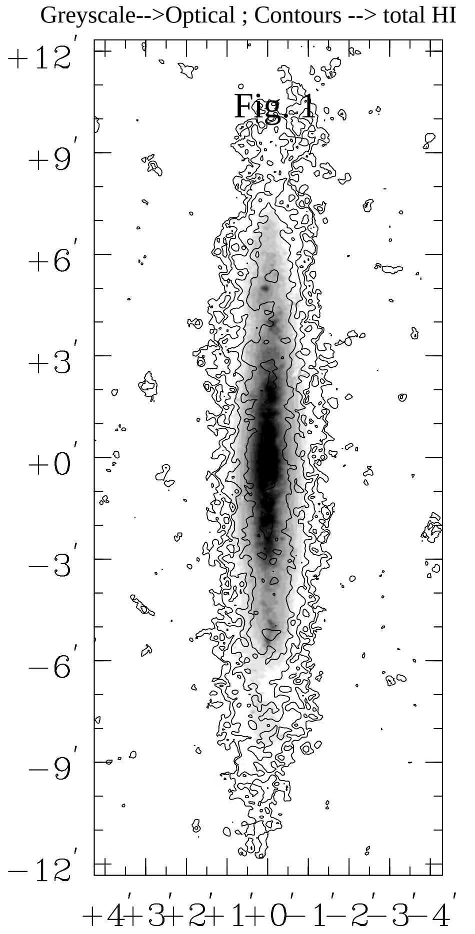
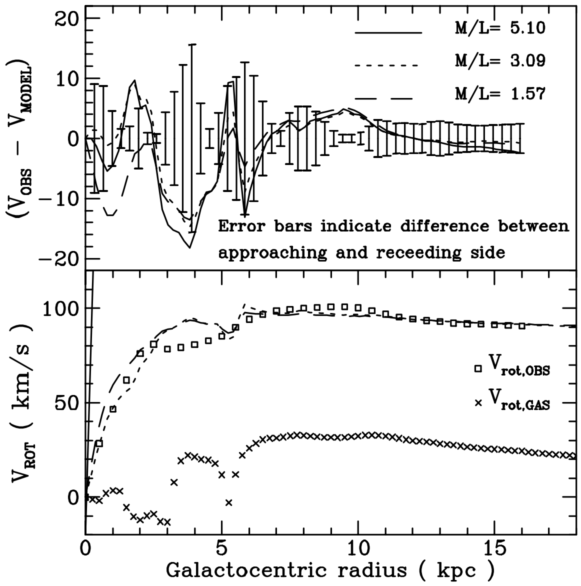


Fig. 2



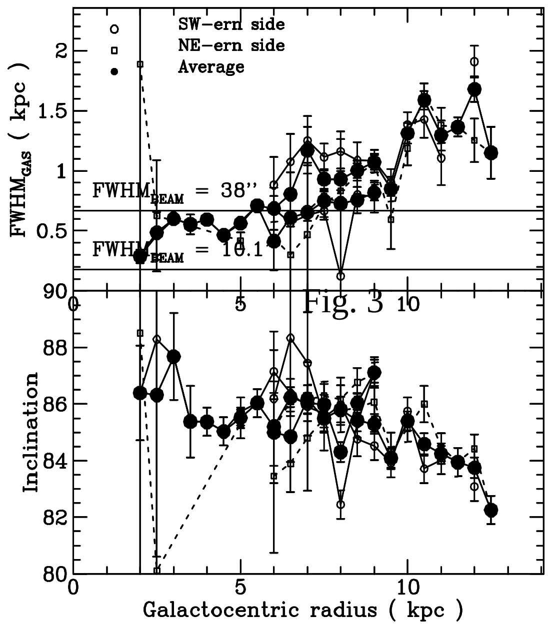


Fig. 4 corrected for gaseous self−gravity