The Flattened Dark Matter Halos of NGC 4244 and the Milky Way

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In a previous paper a method was developed to determine the shapes of dark matter halos of spiral galaxies from the flaring and velocity dispersion of the gas layer. Here I present the results for the almost edge-on Scd galaxy NGC 4244 and preliminary results for the Milky Way. NGC 4244's dark matter halo is found to be highly flattened with a shortest-to-longest axis ratio of $0.2^{+0.3}_{-0.1}$. If the dark matter is disk-like, the vertical velocity dispersion of the dark matter must be $\sim 20\%$ larger than the measured tangential dispersion in the H I. The flaring of the Milky Way's gas layer, the local column of identified stars and the total column within 1.1 kpc from the plane are consistent with a moderately flattened dark halo (E7-E0) and galactic constants of $R_0 = 7.1$ kpc, $\Theta_0 = 180$ km s$^{-1}$, while the stellar disk is $\sim 80\%$ of maximal.

1 Introduction

Although rotation curves of spiral galaxies have been used as evidence for the presence of dark matter (DM), little is known about the nature, extent and actual distribution of the DM in individual galaxies. The equatorial rotation curve, which probes the potential in only one direction, provides no information about the shape of DM halos.

Several methods have been used to determine the shapes of dark matter halos. The analysis of warps shows that only one of the five systems studied requires a DM halo as flattened as E4. On the other hand, in studies of polar ring galaxies substantially flattened DM halos are found (E6-E7 and E5). The shape of the dark halo of the Milky Way...
Way has been estimated from stellar kinematics (E0 - E7; see below). The S0 galaxy NGC 4753 seems to have a rather round DM halo (E1). The X-ray isophotes of two early type galaxies indicate that their dark halos are moderately flattened (E5.5 and E6). Cold dark matter galaxy formation simulations which include gas dynamics tend to produce rather oblate DM halos, with \( q = c/a = 0.5 \pm 0.15 \) (Fig. 1).

Fig. 1. A histogram of the known DM halo shapes. The Dotted line and the filled squares represent the theoretical prediction. The points with error bars represent the individual galaxies. Note the discrepancy between the results from the warping-gas-layer method (rightmost bin) and the other methods.

The shape of the dark halo can be determined by comparing the measured thickness of the gas layer (flaring) with that expected from a self-gravitating gaseous disk in the potential due to the stars and the flattened DM halo. If a round halo, with a certain density distribution, is squeezed along the vertical axis, the densities and the exerted gravitational forces will increase, resulting in a thinner \( \text{H I} \) disk and higher rotation speeds. In order to fit the observed rotation curve, one has to deform the DM-halo such that the DM-halo density \( \rho_{DM} \) at large distances will be roughly inversely proportional to the halo flattening \( q \). Since the thickness of the gas layer beyond the optical disk is proportional to \( 1/\sqrt{\rho_{DM}} \), \( q \sim (\text{width of the gas layer})^2 \).

Below I apply the method to the galaxy NGC 4244 for which the basic parameters were determined in Paper II, and present preliminary
results for the Milky Way.

2 The Method

For a constant temperature gas, the density at height \( z \) above the plane, \( \rho_{\text{gas}}(z) \), can be calculated from the equation of hydrostatic equilibrium:

\[
\sigma_{\text{gas}}^2 \frac{d \ln \rho_{\text{gas}}(z)}{dz} = -K_z(z),
\]

with \( \sigma_{\text{gas}} \) the velocity dispersion. Assuming that the density distribution \( \rho(z) \) extends to infinity (i.e., \( \rho(R, \theta, z) = \rho(z) \)) the potential has only a vertical gradient so that the vertical force can be calculated from the Poisson equation: \( K_z(z) = -4\pi G \int_0^z \rho(z')dz' \). Although not perfect, this plane parallel sheet approximation has been used extensively in the past and can be used for first order approximations to the expected thickness of the gas layer\(^2\). For example, in the cases that the gaseous self-gravity, the stellar disk, or the DM halo dominates the potential the full width at half maximum (FWHM) of the gas layer is given by:

\[
\begin{align*}
\text{FWHM}_{\text{self}}(R) &\approx 1.58 \frac{\sigma_{\text{gas}}}{\Sigma_{\text{gas}}} \\
\text{FWHM}_{\text{stars}}(R) &\approx 0.6 \frac{z_e}{\Sigma_{\text{stars}}} \times \sigma_{\text{gas}} \\
\text{FWHM}_{\text{halo}}(R) &\approx 2.35 \left( \frac{2.4q_\rho}{1.4 + q_\rho} \right) \left( \frac{\sigma_{\text{gas}}}{V_{\text{max}}} \right) \sqrt{R_c(q_\rho)^2 + R^2}
\end{align*}
\]

with \( \Sigma_{\text{gas}} \) and \( \Sigma_{\text{stars}} \) the gaseous and stellar surface densities in units of \( M_\odot \text{pc}^{-2} \), \( z_e \) the scale-height of the stellar disk, \( V_{\text{max}} \) the maximum rotation speed (in km s\(^{-1}\)), \( R_c(q_\rho) \) the core radius of the dark halo, and \( R \) the cylindrical radial distance (all distances in kpc). These equations can be combined to yield an approximate value for FWHM\(_{\text{gas}}\) if more than one component contributes to the potential\(^2\). In regions where the rotation curve rises steeply or the surface density varies rapidly this approximation fails so that it is better to calculate the vertical force from the density distribution of the whole galaxy\(^3\):

\[
K_z(R, z) = G \int_0^\infty r dr \rho(r, 0) \int_{-\infty}^\infty dw \rho_{\text{tot}}(r, w) \int_0^\pi \frac{d}{dz} \frac{d \theta}{|\mathbf{s} - \mathbf{S}|},
\]
with \( \mathbf{s} = \{r, \theta, w\} \), \( \mathbf{S} = \{R, 0, z\} \). I incorporate three components in the
global mass model; 1) a stellar disk with a density distribution which
decreases exponentially with radius and height above the plane; 2) a
non-singular flattened isothermal DM-halo with core radius \( R_c(q_\rho) \) and
central density \( \rho_0(q_\rho) \) with a density distribution proportional to \( 1/R^2 \)
to reproduce the observed “flat” rotation curves; and 3) a gaseous disk.

Of course, the true DM-halo density distribution may be different.\(^{25}\)
However, for roundish DM distributions the vertical force is roughly pro-
portional to the radial force which is the same for all disk-halo combina-
tions that reproduce the observed rotation curve, so that at large radii
the width of the gas layer is independent of the radial distribution of
the DM. The flattening of the DM halo introduces a \( \sim \sqrt{q_\rho} \)-dependence
on the thickness of the gas layer.

Comparing the thickness of the gas layer beyond the optical disk
with model flaring curves, calculated for a series of models with varying
halo flattening, then yields the halo shape.

3 Results: NGC 4244

The Scd galaxy NGC 4244 was observed for 14 hours with the VLA\(^\dagger\) to
determine the gaseous velocity dispersion and the rotation curve. While
compact, fast rotating galaxies are known to have declining rotation
curves,\(^{10,29}\) NGC 4244 is the only low mass galaxy (\( V_{max} \approx 100 \text{ km s}^{-1} \))
for which the rotation curve falls, in Keplerian fashion.

A new technique\(^{27}\) has been used to determine the width of the gas
layer (Fig. 2). An upper limit to \( FWHM_{\text{gas}} \) is found by assuming a
constant inclination of 84°5, while incorporating the slight warp into the
analysis yields the best values for the flaring (filled triangles).

Comparing the observations with the model flaring curves (drawn
lines), I conclude that the DM halo of NGC 4244 is highly flattened \( q_\rho = 0.2 \pm 0.1 \). This flattening, the most extreme value reported to
date, lies at the extreme end of the theoretical predictions (Fig. 1). Is

\(^{\dagger}\) The VLA of the National Radio Astronomy Observatory is a facility of the Na-
tional Science Foundation operated under cooperative agreement by Associated Uni-
versities, Inc.
it possible that some systematic effect plays a role and that NGC 4244’s DM halo is less flattened? I investigate several possibilities: a) The systematics introduced by the uncertainty in the inclination is discussed in the caption of Fig. 1. b) Non-thermal pressure gradients due to magnetic fields and cosmic ray heating [which add to the LHS. of Eqn (1)] are unlikely to be important beyond the optical disk because cosmic rays are closely related to sites of star formation. If they are important an even denser, i.e. flatter, DM halo would be required to have a gas layer as thin as observed. And c) If the vertical velocity dispersion is smaller than the measured planar dispersion, the DM halo would be rounder than inferred above. There is no observational evidence that such might be the case. Furthermore, because the interstellar medium is likely to be in the warm neutral phase due to the low pressure, the short collision times (≤ 10⁵ year) preclude any anisotropy in the velocity dispersion tensor. We conclude that the DM halo of NGC 4244 is significantly flattened, with \( q_ρ = 0.2^{±0.3}_{−0.1} \).
3.1 An Alternative Explanation?

Pfenniger et al. reviewed disk-like molecular hydrogen as a dark matter candidate. The fact that in many galaxies the shape of the rotation curve due to the gas is similar to the observed rotation curve could then be explained if \( \sim 6\% \) of the gaseous surface density is in atomic form. Since the self-gravity of the gas layer beyond the optical disk strongly affects the flaring (Eqn 2) I investigate whether the cold gas hypothesis is consistent with NGC 4244’s flaring curve. In order for the dark disk to have a thickness equal to the H I layer, the vertical velocity dispersion of the dark disk must be \( \sim 20\% \) larger than the dispersion in the H I. Furthermore, to avoid radial instabilities, the planar velocity dispersion has to be 20\% - 100\% larger than the vertical dispersion: a dark disk requires an anisotropic velocity dispersion tensor.

4 Results: The Milky Way

The flaring of the Milky Way’s gas layer can be used to constrain the shape of the dark matter halo as well. The analysis is complicated however because the uncertainties in the distance to the galactic center \( (R_0) \), the rotation speed at the solar circle \( (\Theta_0) \), and the scale-length of the stellar mass \( (h_R) \). Sackett reviewed these values and found the following: \( R_0 = 7.8 \pm 0.7 \) kpc, \( \Theta_0 = 200 \pm 20 \) km s\(^{-1}\), and \( h_R = 3 \pm 1 \) kpc. Due to independent constraints on the Oort constants \( A - B (= \Theta_0 / R_0) \) and \( A \), small values for \( R_0 \) requires small values for \( \Theta_0 \), and vice-versa. I calculated flaring curves for Milky Way models with a small, intermediate and large value for \( R_0 \): \( (R_0,\Theta_0) = (7.1, 180) \), \( (R_0,\Theta_0) = (7.8, 200) \), and \( (R_0,\Theta_0) = (8.5, 220) \). These Milky Way models include a stellar bulge and disk which is truncated at around \( (R_0 + 4.5) \) kpc. Various authors reported on the thickness and column- and volume densities of the H I & H\(_2\) layers of the Milky Way. These observations were all scaled using a fit to the rotation curve of the inner and outer Milky Way, scaled separately for the three \( R_0 \) and \( \Theta_0 \) combinations. Since the models which predict the thickness of the gas layer cannot handle a multi-component interstellar medium, the Milky Way’s flaring data must be compared with the
model predictions beyond the solar circle, where the H$_2$ column densities are small. In the model calculations I used the velocity dispersions of the H I (9.2 km s$^{-1}$) as determined in the inner galaxy.

Fig. 3 compares the observed thickness of the gas layer with model predictions for various halo flattenings. Only those model flaring curves are plotted for which the column density in identified stars (35 ± 5 $M_\odot$ pc$^{-2}$) and the total column density within 1.1 kpc from the plane (71 ± 6 $M_\odot$ pc$^{-2}$) are within 3-σ of the nominal values.

Fig. 3. The flaring of the Milky Way (triangles) superposed on model flaring curves with different halo shapes. For this assumed $R_0$ -Θ$_0$ combination, the rotation curve has been determined till 18 kpc, and extrapolated beyond. The last three data points are thus least reliable. This disk model is 70% ($\gamma = 0.70$) of maximal. The errors are not random errors, but are calculated by averaging the measurements of various authors (3 for $R \leq 18$ kpc, 2 beyond). The three values plotted to the right of the model curves indicate: a) the halo flattening, b) the difference between the model and observed (stars+gas+halo) surface density within 1.1 kpc, and c) the difference between the model stellar column density and the column of identified stars (in units of their rms uncertainties).

Model calculations with an optical scale-length of 2 kpc yield a somewhat better correspondence between model and flaring data; longer scale-lengths fit somewhat worse. The same is true for Milky Way models with larger values for $R_0$. Because the errors on the observed widths
are systematic, no formal determination of the dark halo flattening can be made. For \( R_0 = 7.1 \) kpc, halo flattenings between 0.3 and 1.0 are consistent with the observed flaring. For larger values of \( R_0 \), the correspondence between the model curves and observations become progressively worse, while the inferred value for \( q_\rho \) increases with \( R_0 \) as well: \( q_\rho = 0.75 \pm 0.25 \) for \( R_0 = 7.8 \) kpc. For \( \Theta_0 = 220 \) km \( s^{-1} \), the model flaring curves lie below the observations for all choices of \( R_0 \), halo flattening and optical scale-length.

The inferred halo flattening depends only slightly upon the actual values of the scale-length of the disk and its \( M/L \) because the halo flattening influences the thickness of the gas layer only beyond the optical disk. While mass models with \( h_R = 3 \) kpc require stellar disks which are \((60 \pm 10)\% \) of maximal, a disk with an optical scale-length of 2 kpc requires \( \gamma \sim 0.9 \pm 0.05 \).

For any given mass model, the midplane dark matter mass density at the solar circle is found to be proportional to \( q^{-0.72 \pm 0.02} \), with an average value of: \( \rho(z = 0; q = 1) = (9.4 \pm 2) \times 10^{-3} \) \( M_\odot \text{pc}^{-3} \). Due to the strong \( q_\rho \)-dependence of \( R_c(q_\rho) \), the halo midplane density depends more strongly upon \( q_\rho \) near the center of the Galaxy than at large radii (where \( \rho_{DM}(z = 0) \propto q^{-0.5} \)).

This determination of the flattening of the Milky Way’s dark halo \((0.65 \pm 0.35)\) is consistent with previous determinations \(4, 36, 23, 2 \) and insensitive to the stellar mass distribution. The major uncertainty is the value of the gaseous velocity dispersion: a 15\% smaller dispersion would yield a round halo. These preliminary calculations favour Galaxy models with low rotation speed and a small distance to the Galactic center.

5  Looking Ahead

I have presented the results of a new method to determine the shape of dark matter halos from sensitive \( \text{H} \) \( \text{I} \) measurements and careful modeling. The first results exclude neither cold dark matter nor disk-like, baryonic dark matter. With current technology and “reasonable” observing times, the thickness of the \( \text{H} \) \( \text{I} \) layer can be measured for galaxies closer than \( \sim 15 \) Mpc at inclinations \( \gtrsim 60^\circ \). I recently observed seven more systems (NGC 2366, 2403, 2903, 2841, 3521, 4236, and 5023) for
which I will try to determine the DM halo shapes. Furthermore, the analysis of the flaring of the gas layers of M31 is in progress. With this increased sample it will be possible to gauge the significance of the highly flattened halo of NGC 4244 and, hopefully, put more stringent constraints on the nature of the dark matter.

Acknowledgements

Most of the work presented here was part of my thesis project at Columbia University. I thank my advisor Jacqueline van Gorkom, Penny Sackett for providing me with the disk-like surface density distributions, and Mike Merrifield for suggestions to improve this contribution. This work was supported in part through an NSF grant (AST-90-23254 to J. van Gorkom) to Columbia University and PPARC grant GR/K58227. And of course I would like to thank Dr. Ramachers and Prof. Klapdor-Kleingrothaus for a superbly organized conference and the Max-Planck-Institut für Kernphysik conference for financial support.

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