Estimates of the Enclosed Mass and its Distribution

for several Spiral Galaxies

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Abstract

Recently, high quality rotation curves for several spiral galaxies have become available from THINGS: **T**he **HI N**earby **G**alaxy **S**urvey (Reference 1).   This paper analyzes 11 of those galaxy rotation curves using the Newtonian Disk Model (Reference 2). The Model assumes that virtually all the mass of stars, gas, dust and dark-matter is contained as a "flattened" mass within the galactic disk, which extends out to the edge of the observable rotation. Estimates of the enclosed mass and its radial distribution are provided.

Introduction

The high quality HI rotation curves from THINGS (Reference 1) span a wide range of spiral galaxy type, mass, and basic characteristics. These galaxies have been extensively analyzed in Reference 1, using the traditional separate mass components of stellar disk, stellar nuclear bulge, HI gas disk and an assumed spheroidal dark-matter halo. These component velocities are added in quadrature to match the rotation curve velocities.

In contrast to the traditional approach, this paper utilizes the Newtonian disk model described in Reference 2. This model assumes that virtually all the galaxy mass is contained within a flattened disk; that includes the stellar disk, stellar

nuclear bulge, gas disk and dark-matter components. There is no spheroidal dark-matter halo in this model.   By adjusting the 12 ring masses, the model is able to produce a rotation curve that matches the individual rotation curve from the THINGS galaxy data.   It is then possible to calculate the enclosed galaxy mass, display its radial distribution, calculate the surface mass density and disk radius of gyration.

Notation

This listing provides symbol notation as used in the Newtonian model of Reference 2.

D Distance to galaxy ~ Mpc

F_d Gravitational Force in disk, toward galaxy center

F_p Gravitational Force in disk if M_m is a point mass at galaxy center

$(F_d/F_p)_m$ Gravitational Force ratio at R_m

G Gravitational Constant   ~ 4.3 x 10^{-6} kpc $(\frac{km}{s})^2 M_{\odot}^{-1}$

I_m Moment of Inertia of galaxy disk $=\sum m_i r_i^2$

m_i Mass of ring i

M_m Enclosed Mass of galaxy disk   = $\sum m_i$ = $(R_m \times V_m^2)/(G \times (F_d/F_p)_m)$

Msun, $M_{\odot}$ Solar Mass

R_g Radius of Gyration of galaxy disk $R_g^2 = I_m/M_m$

R_m Outermost radius of observed galaxy rotation   ~ kpc

SMD Surface Mass Density at given disk location   ~ $M_{\odot}/pc^2$

SMD_{av} Average SMD in galaxy disk   = $M_m/(\pi R_m^2)$

V_m Circular Velocity in galaxy disk at R_m ~ km/s

The Galaxy Sample

Rotation curves from eleven spiral galaxies of the THINGS data have been chosen for analysis and are listed in Table 1.

Galaxy	Type	D	R_m	V_m	$(F_d/F_p)_m$	M_m	SMD_{av}	R_g/R_m
		Mpc	kpc	km/s		$10^{10}M_\odot$	$M_\odot/pc^2$	
NGC 925	SBd	9.2	13	120	1.82	2.39	45	0.58
NGC 2841	Sb	14.1	34.8	288	1.54	43.6	115	0.47
NGC 2903	SBd	8.9	29	183	1.46	15.5	59	0.45
NGC 3031	Sab	3.6	14.8	196	1.32	10.0	146	0.41
NGC 3198	SBc	13.8	38	154	1.55	13.5	30	0.49
NGC 3521	SBc	10.7	31.2	204	1.53	19.7	65	0.45
NGC 4736	Sab	4.7	10.3	115	1.21	2.63	79	0.35
NGC 4826	Sab	7.5	22	155	1.52	8.10	53	0.48
NGC 5055	Sbc	10.1	48.8	170	1.34	24.4	33	0.43
NGC 6946	Scd	5.9	19.1	199	1.54	11.4	100	0.50
NGC 7793	Sd	3.9	7.7	100	1.40	1.28	69	0.48

Table 1.   Spiral Galaxy Characteristics

The galaxies in Table 1 are at distances between 3 and 15 Mpc, and have typical linear resolutions between ~100 and ~500 pc. The radio synthesis measurements of the velocities across the entire HI filled disks, provide an unusual sample of galaxies analyzed and modeled in a uniform way at sub-kpc resolution. Reference1 shows the rotation curve data for the individual galaxies. A "faired" line can be drawn through the data, and then approximately 20 points are extracted to provide the required values for the Newtonian model.

For each of the galaxies in Table 1, Figures 1 through 11 show the estimated galaxy mass and its distribution.   These Figures have been grouped together to provide easy cross-reference and comparison. The upper chart for each galaxy shows the rotation curve extracted from THINGS (Reference 1) as a solid-black

curve.   The dashed-red curve shows how well the Newtonian model matches the galaxy data. This upper chart also notes the estimated galaxy mass, and the distance D associated with the galaxy disk radial dimensions. The galaxy mass varies directly with the disk size, Rm, and therefore varies directly with the assumed distance D. When comparing results of this paper with other studies, it is necessary to adjust values based on the assumed distance in those studies.
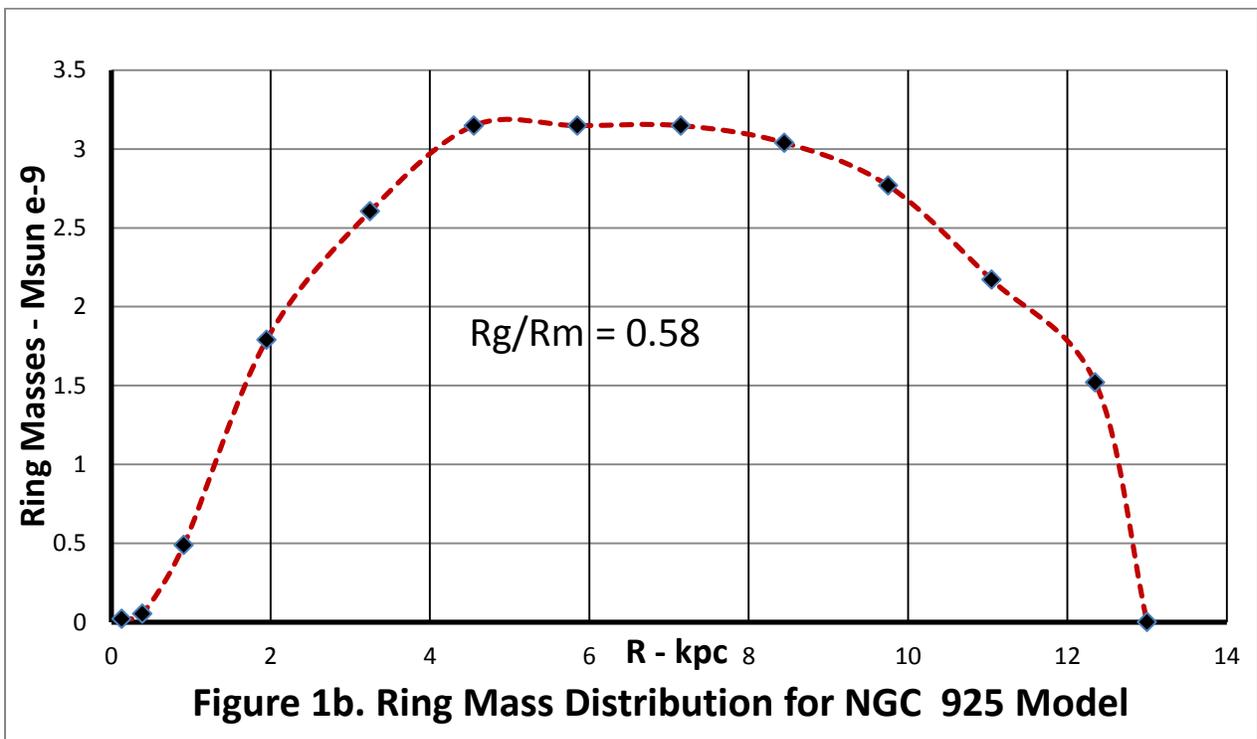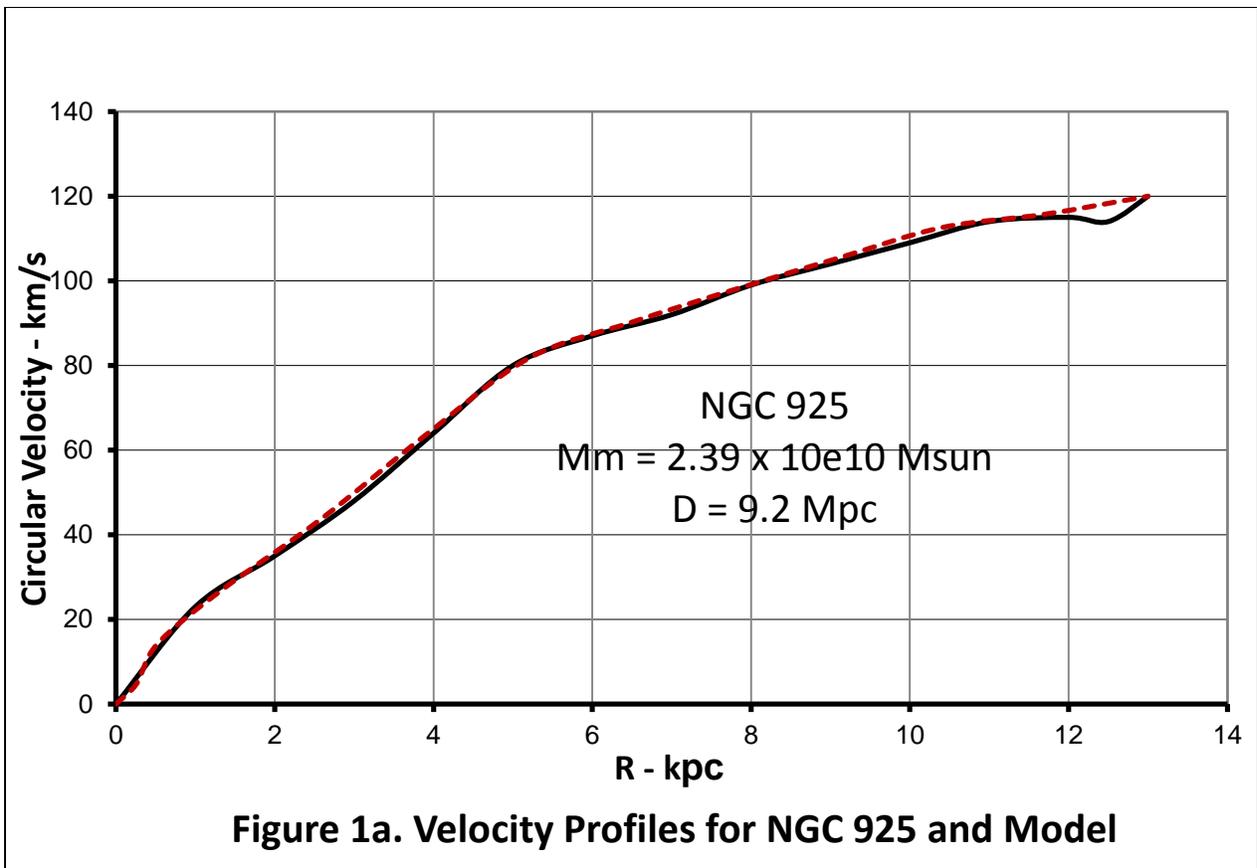
The lower chart for each galaxy model shows the radial distribution of the Ring Masses that produce the model rotation curve.   Also included in the lower chart is the Rg/Rm gyration ratio of the mass distribution.
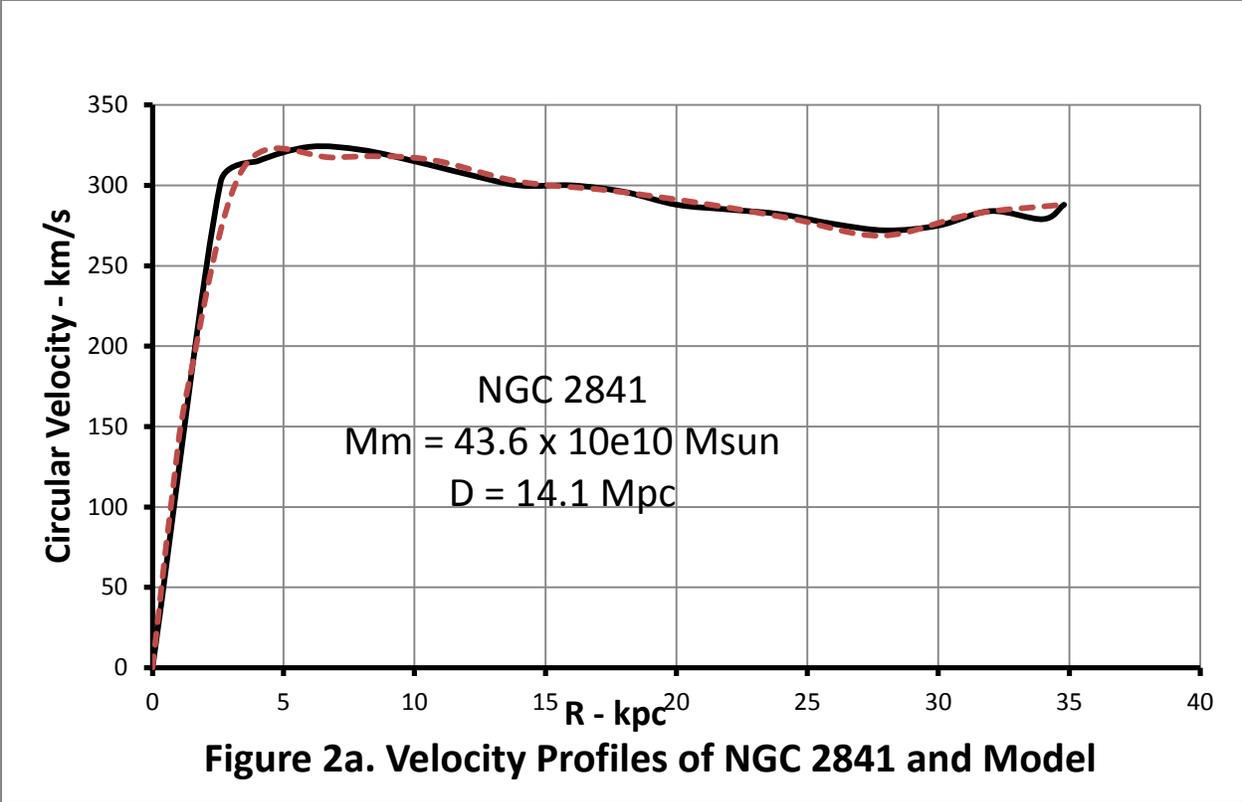
Discussion

Reviewing Figures 1 through 11, it can be seen that the model achieves a reasonable match with the galaxy rotation curves.   With only 12 ring masses, the current model does not match all the minor undulations in some of the observed rotation curves.   Given the approximations involved in defining the observed rotation curves, the current model is considered to provide satisfactory rotation curve matching.

The ring mass distribution for the individual galaxies and the Rg/Rm ratios show that the galaxy mass is well dispersed radially in the galaxy disk. This dispersion is in marked contrast with the solar system, where over 99% of the system mass is contained within the sun, and the system gyration radius is deep below the surface of the sun.

Most of these galaxies have relatively straightforward rotation curves and many have been the subject of earlier analyses, as noted in Reference 1.   However, NGC 4826 has the unusual feature that HI gas in the outer disk rotates in the opposite direction to the HI gas in the inner disk. This feature is considered evidence of a collision and merging of two galaxies millions of years ago.   There is a transition phase (4 kpc<R<12 kpc) in the rotation curve between the inner and outer disks, which shows some confused and non-circular motions. It is difficult to define the rotation curve in this transition phase, so the model estimates of galaxy mass for NGC 4826 should be regarded as tentative only.

Figure 1a. Velocity Profiles for NGC 925 and Model

NGC 925
Mm = 2.39 x 10e10 Msun
D = 9.2 Mpc

Rg/Rm = 0.58

Figure 1b. Ring Mass Distribution for NGC 925 Model

Figure 2a. Velocity Profiles of NGC 2841 and Model

NGC 2841
Mm = 43.6 x 10e10 Msun
D = 14.1 Mpc

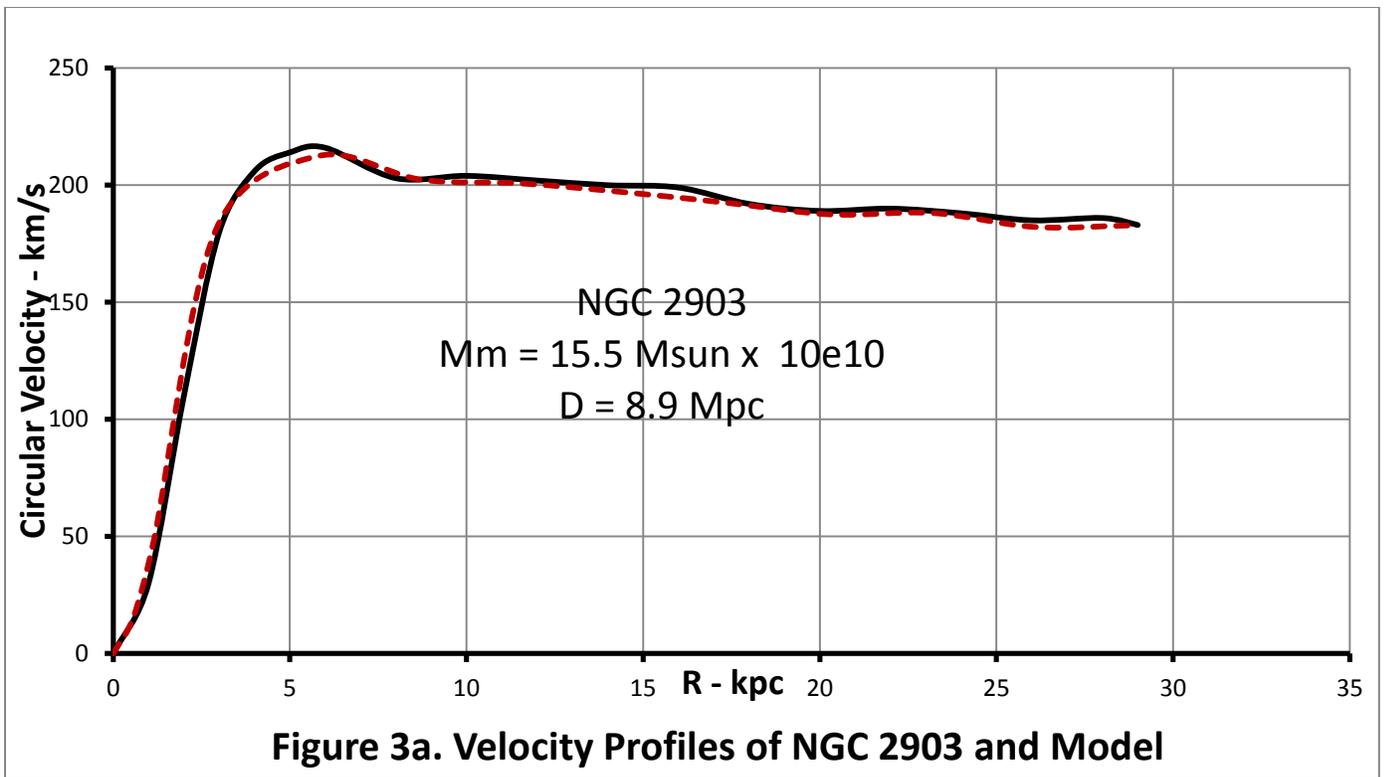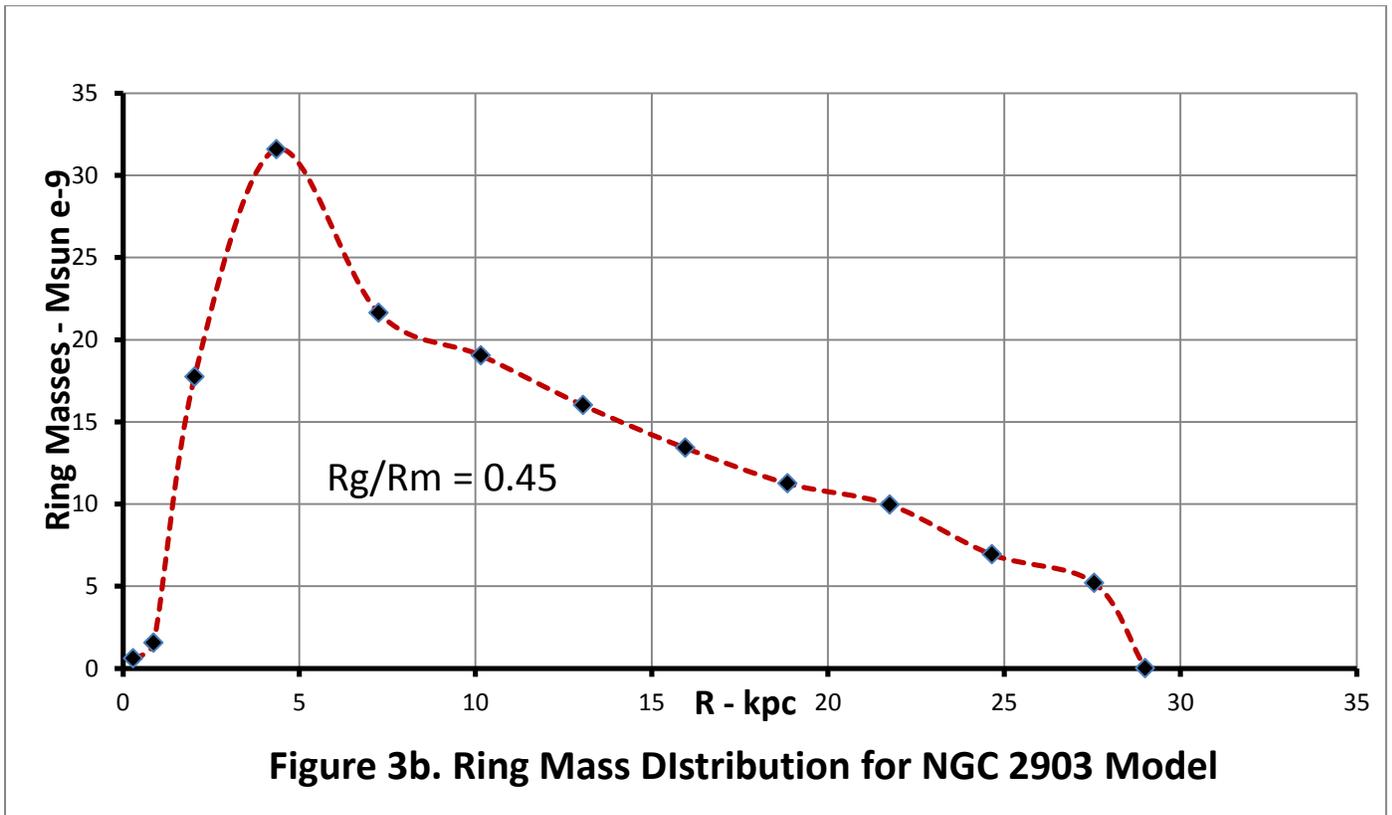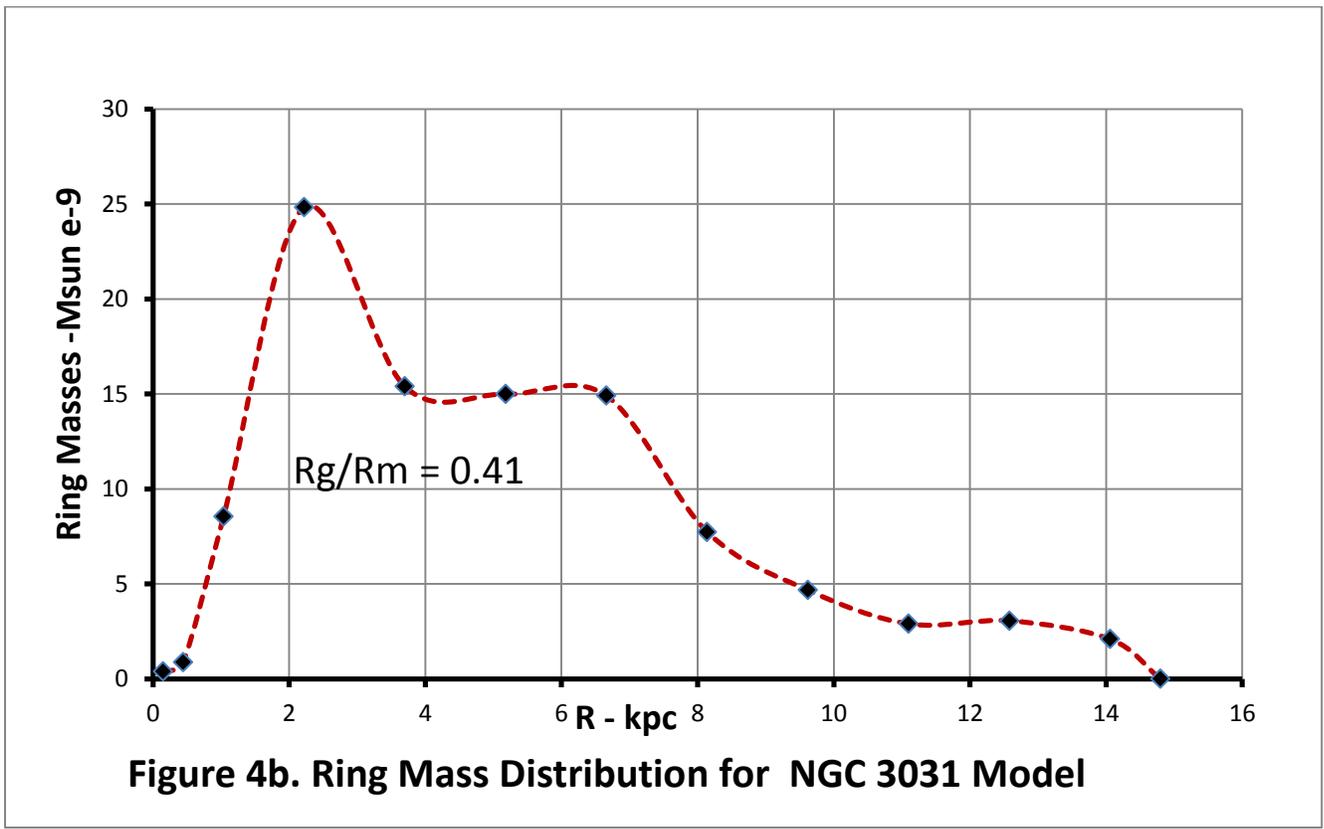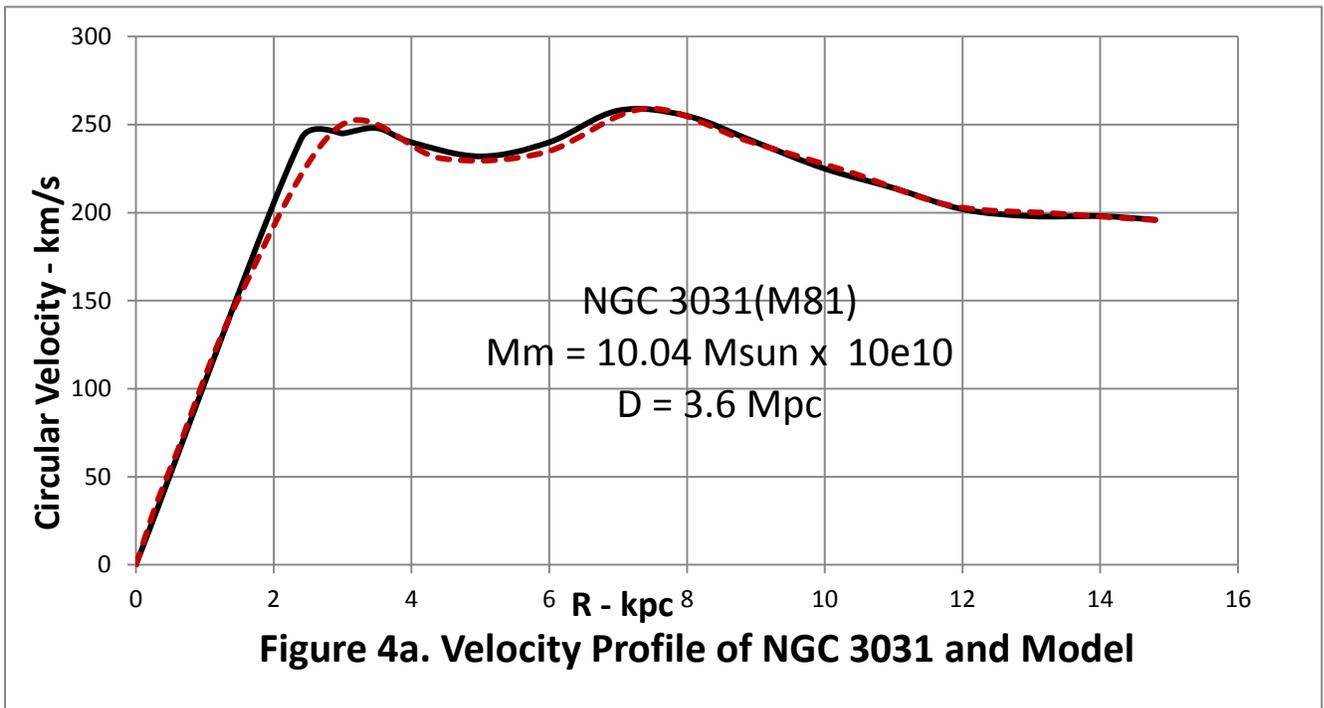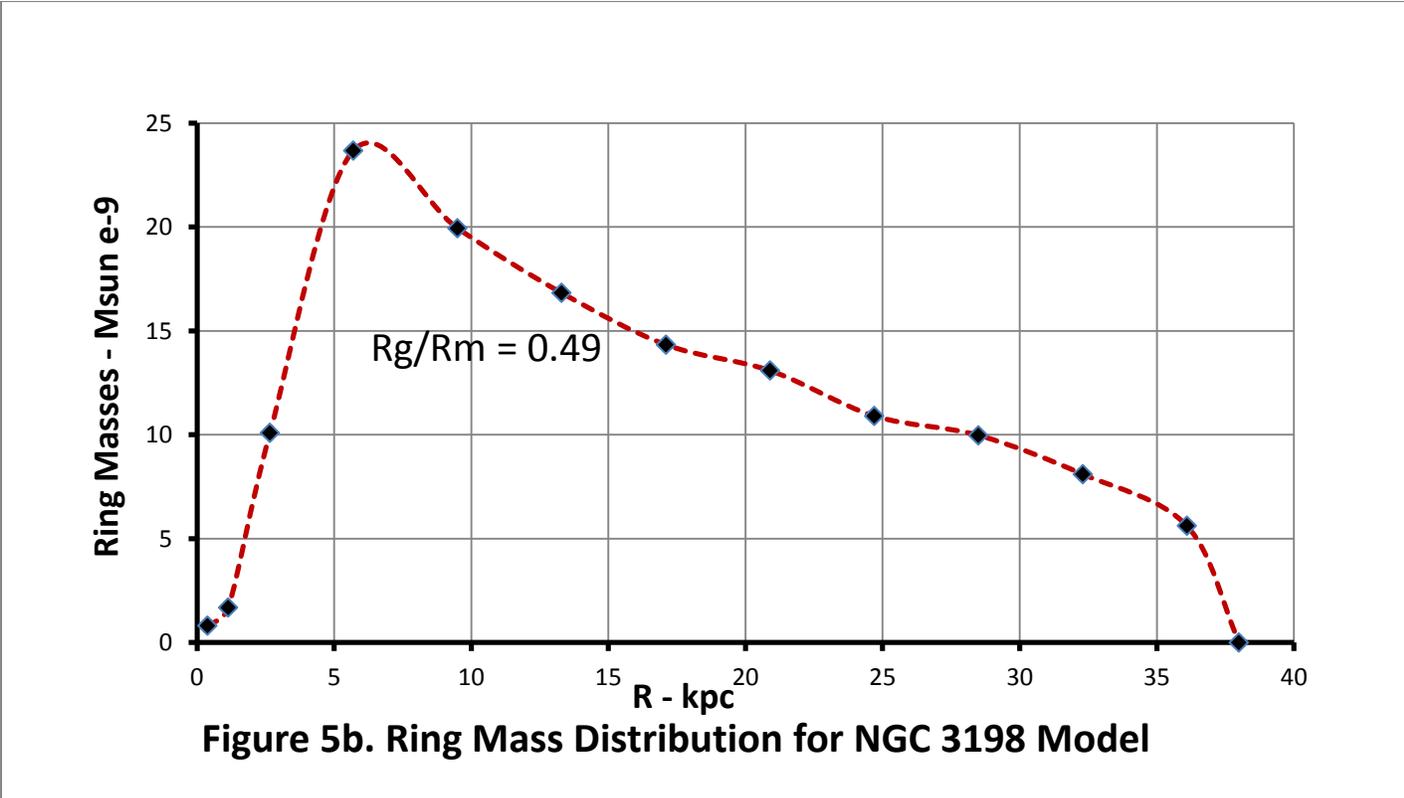Rg/Rm = 0.47

Figure 2b. Ring Mass Distribution for NGC 2841 Model
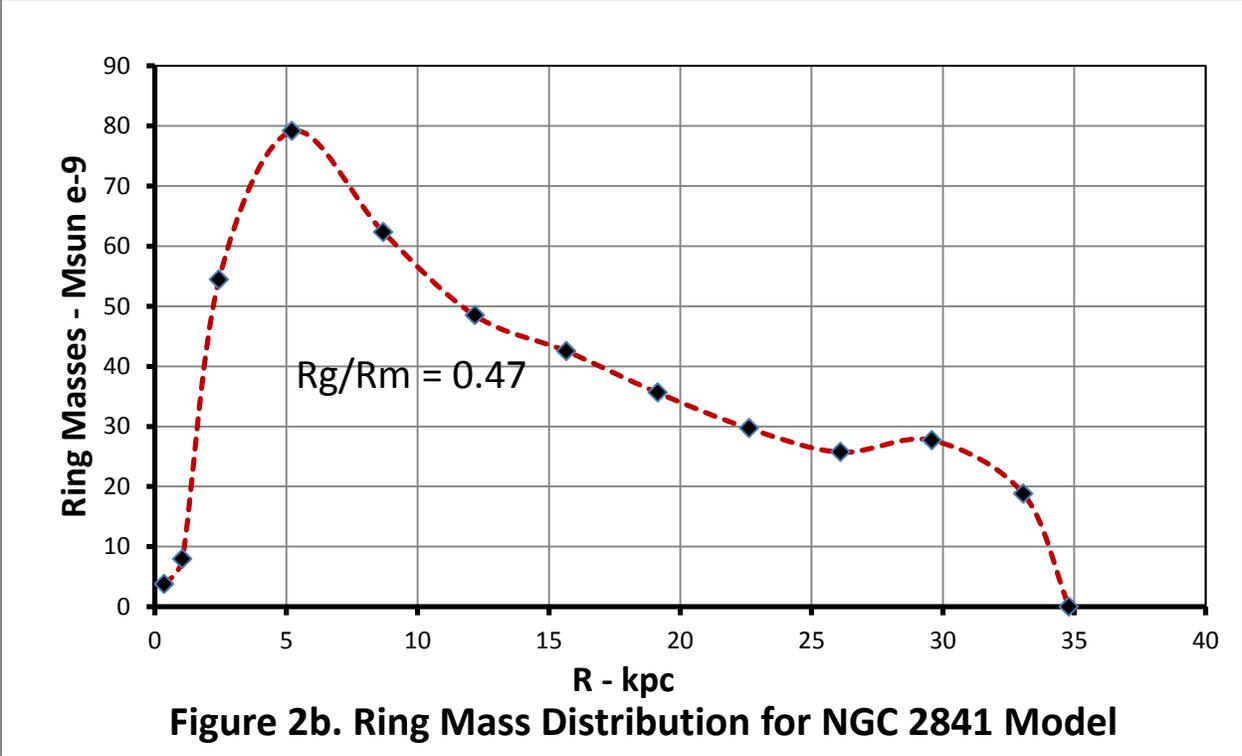
Figure 3a. Velocity Profiles of NGC 2903 and Model

NGC 2903
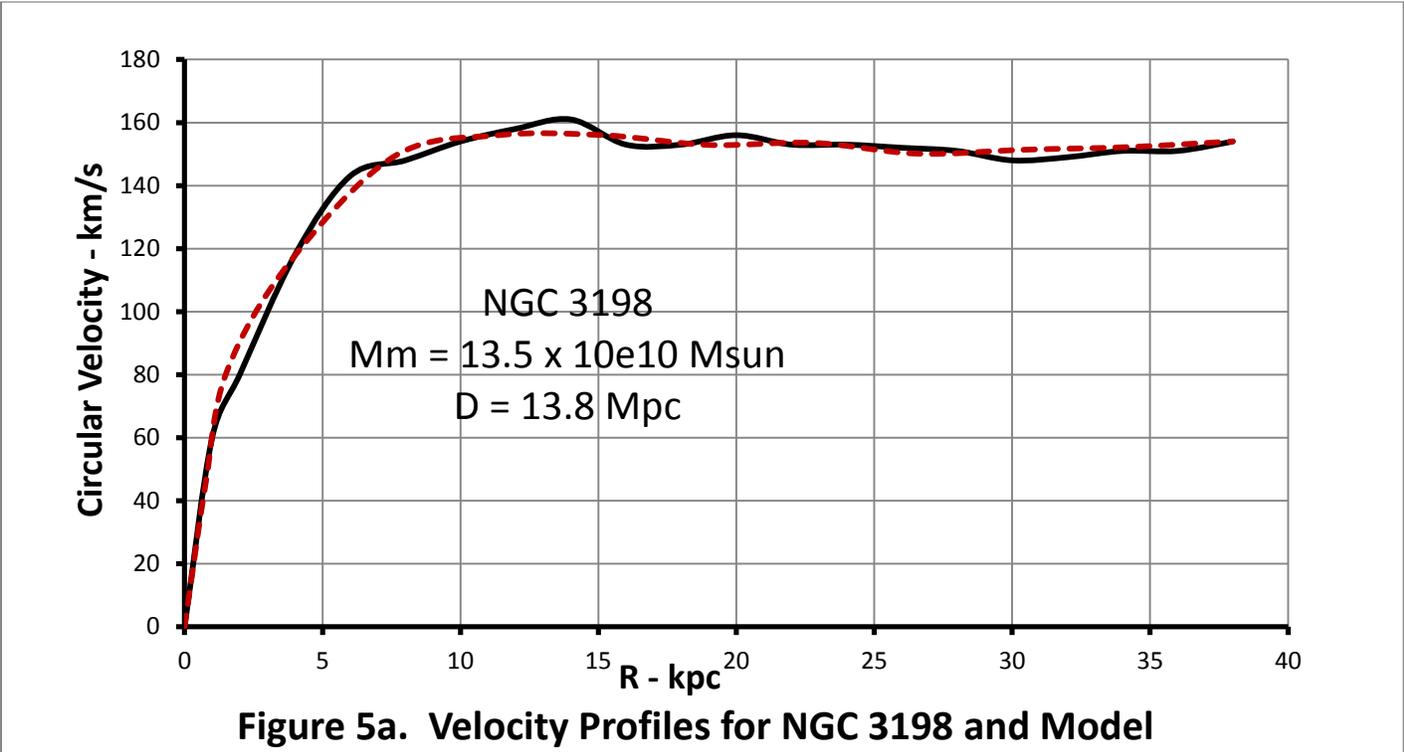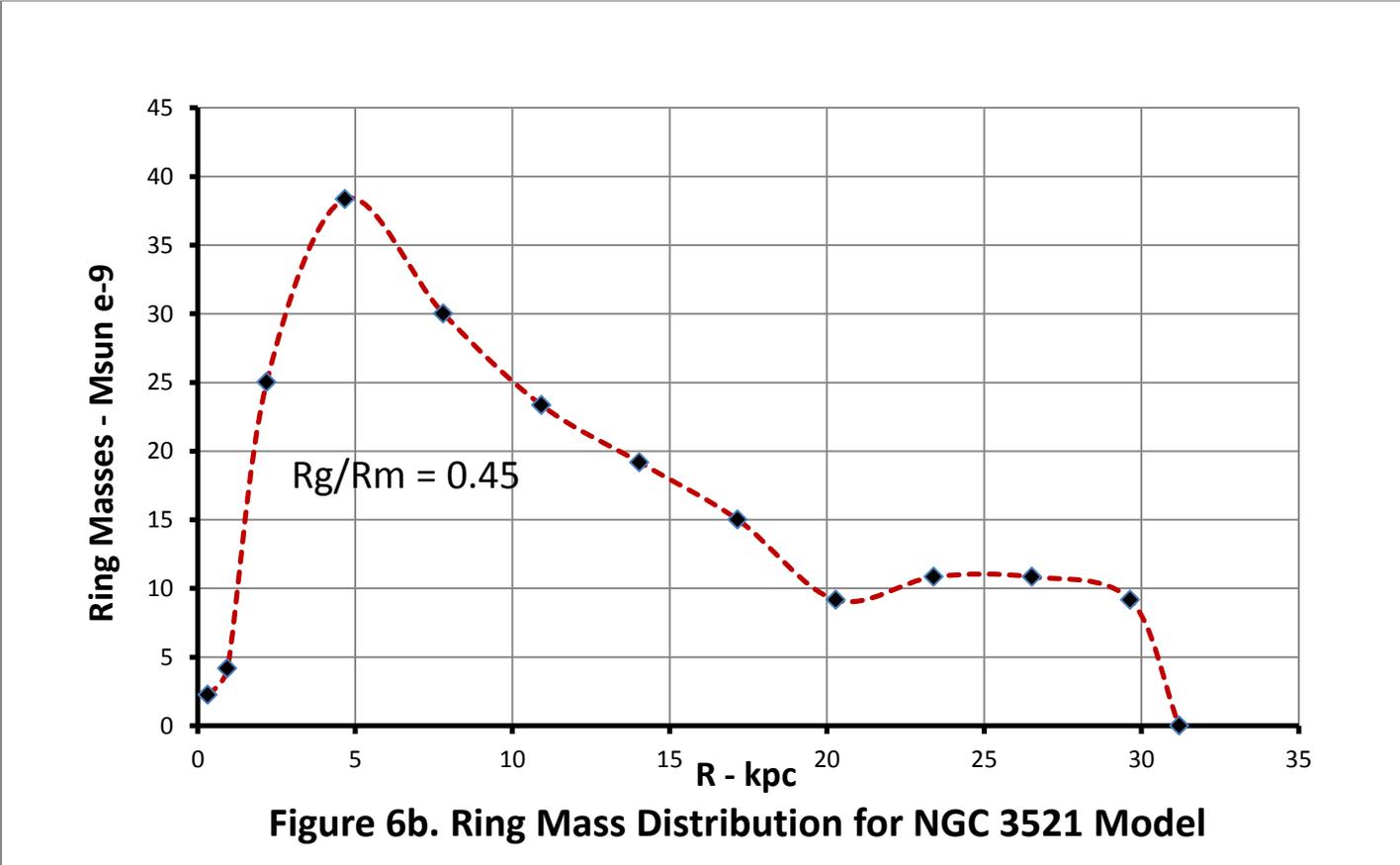Mm = 15.5 Msun x 10e10
D = 8.9 Mpc

Rg/Rm = 0.45

Figure 3b. Ring Mass DIstribution for NGC 2903 Model

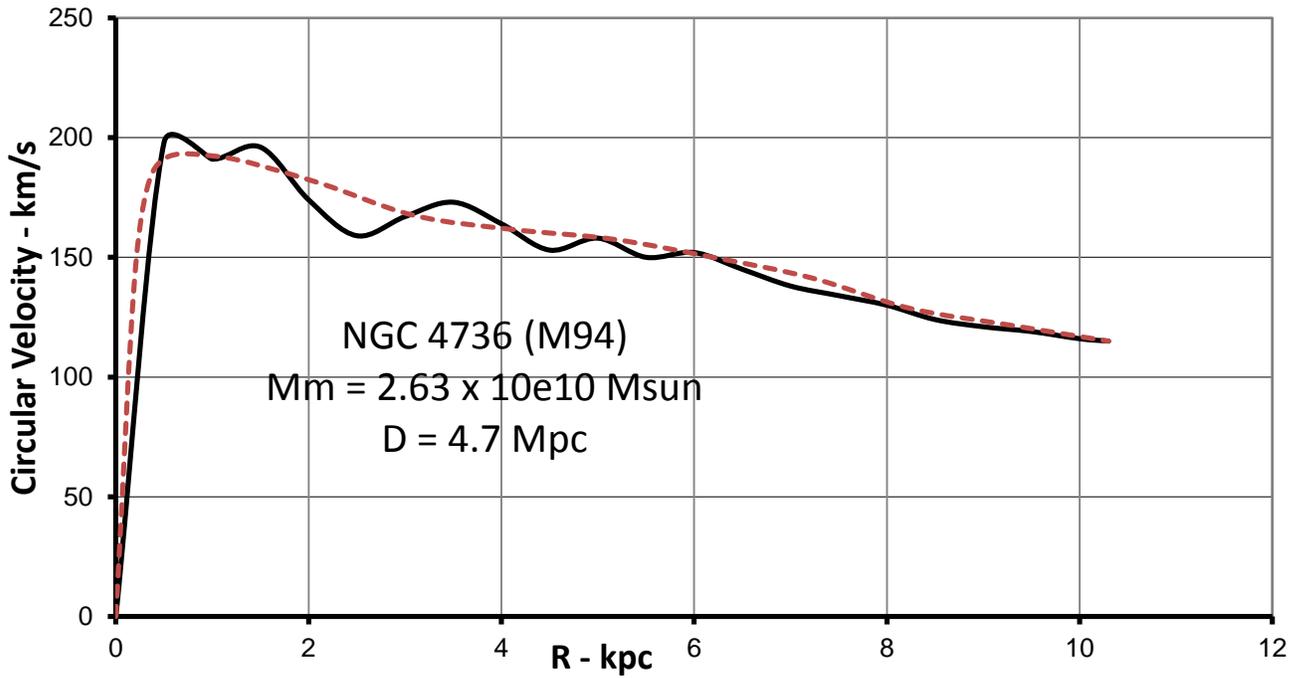**Figure 4a. Velocity Profile of NGC 3031 and Model**

NGC 3031(M81)

Mm = 10.04 Msun x 10e10

D = 3.6 Mpc

Rg/Rm = 0.41

Figure 4b. Ring Mass Distribution for NGC 3031 Model

Figure 5a. Velocity Profiles for NGC 3198 and Model

NGC 3198
Mm = 13.5 x 10e10 Msun
D = 13.8 Mpc

Figure 5b. Ring Mass Distribution for NGC 3198 Model

Rg/Rm = 0.49

Figure 6a. Velocity Profiles for NGC 3521 and Model

NGC 3521
Mm = 19.7 x 10e10 Msun
D = 10.7 Mpc

Rg/Rm = 0.45

Figure 6b. Ring Mass Distribution for NGC 3521 Model

Figure 7a. Velocity Profiles of NGC 4736 and Model

NGC 4736 (M94)
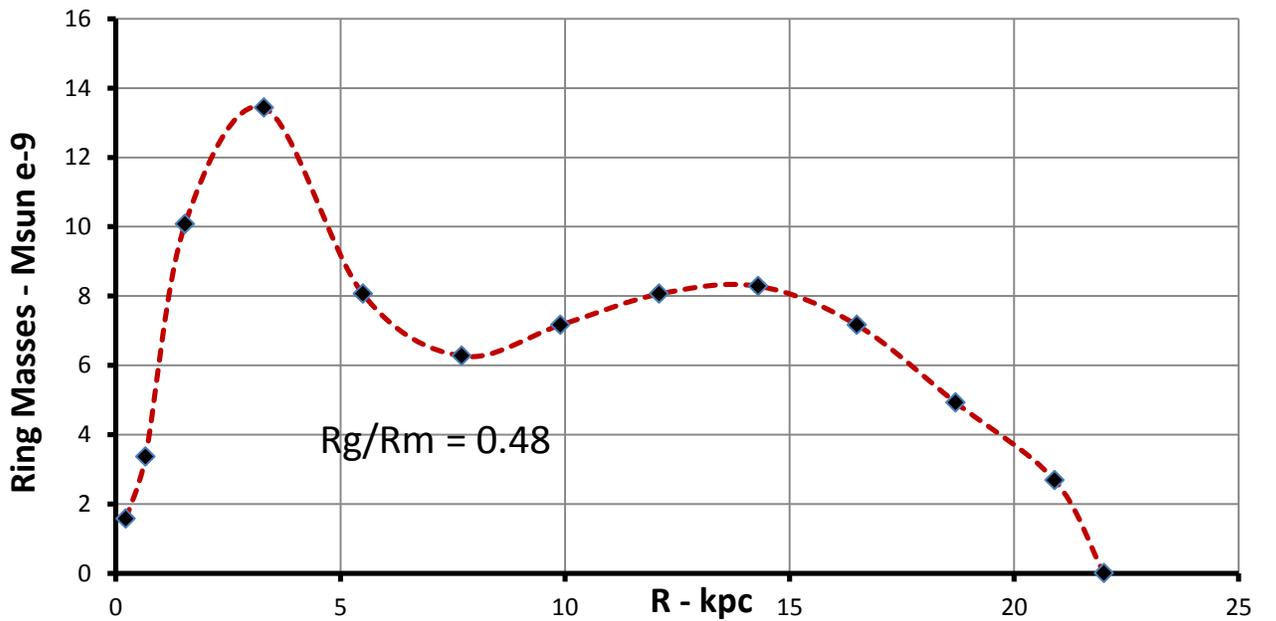Mm = 2.63 x 10e10 Msun
D = 4.7 Mpc

Rg/Rm = 0.35
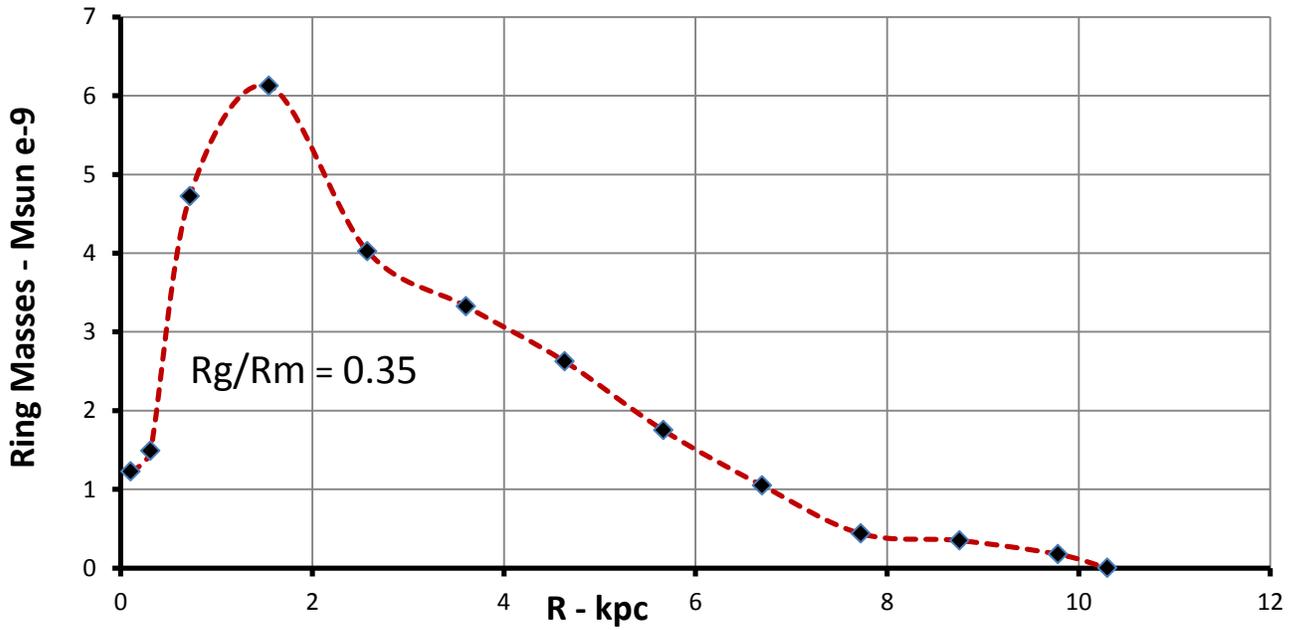
Figure 7b. Ring Mass Distribution for NGC 4736 Model
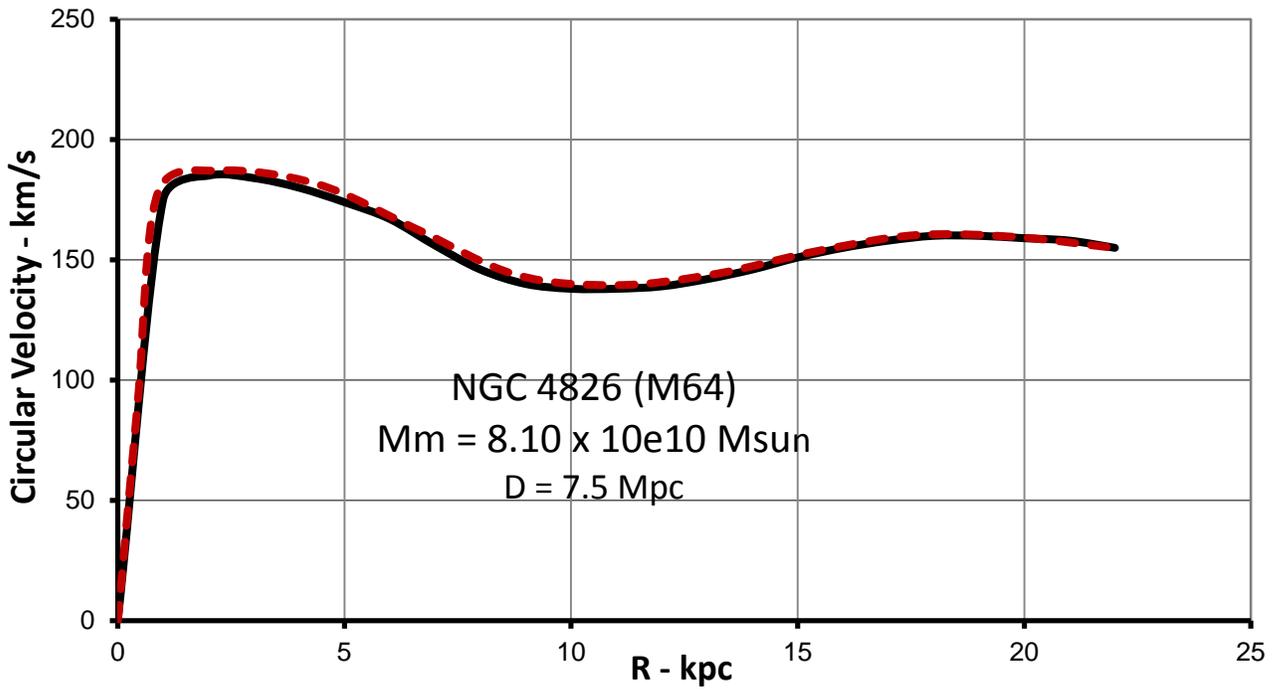
Figure 8a. Velocity Profiles of NGC 4826 and Model

NGC 4826 (M64)
Mm = 8.10 x 10e10 Msun
D = 7.5 Mpc

Figure 8b. Ring Mass Distribution for NGC 4826 Model

Rg/Rm = 0.48
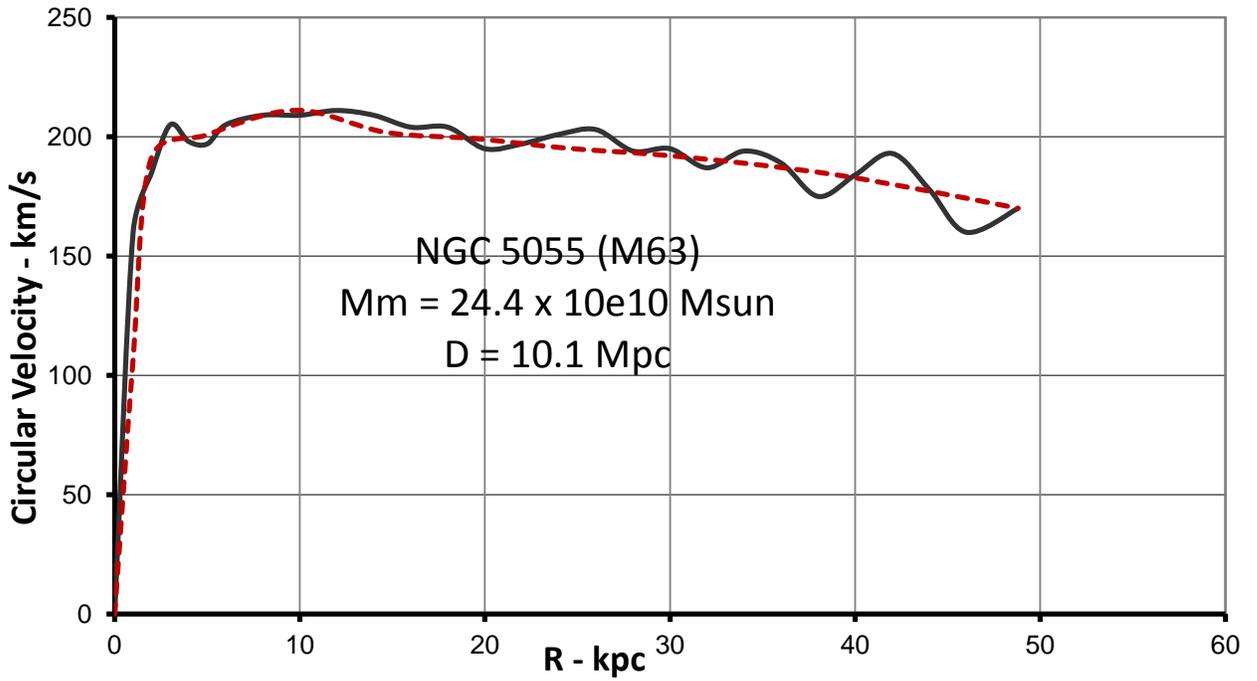
Figure 9a. Velocity Profiles of NGC 5055 and Model

NGC 5055 (M63)
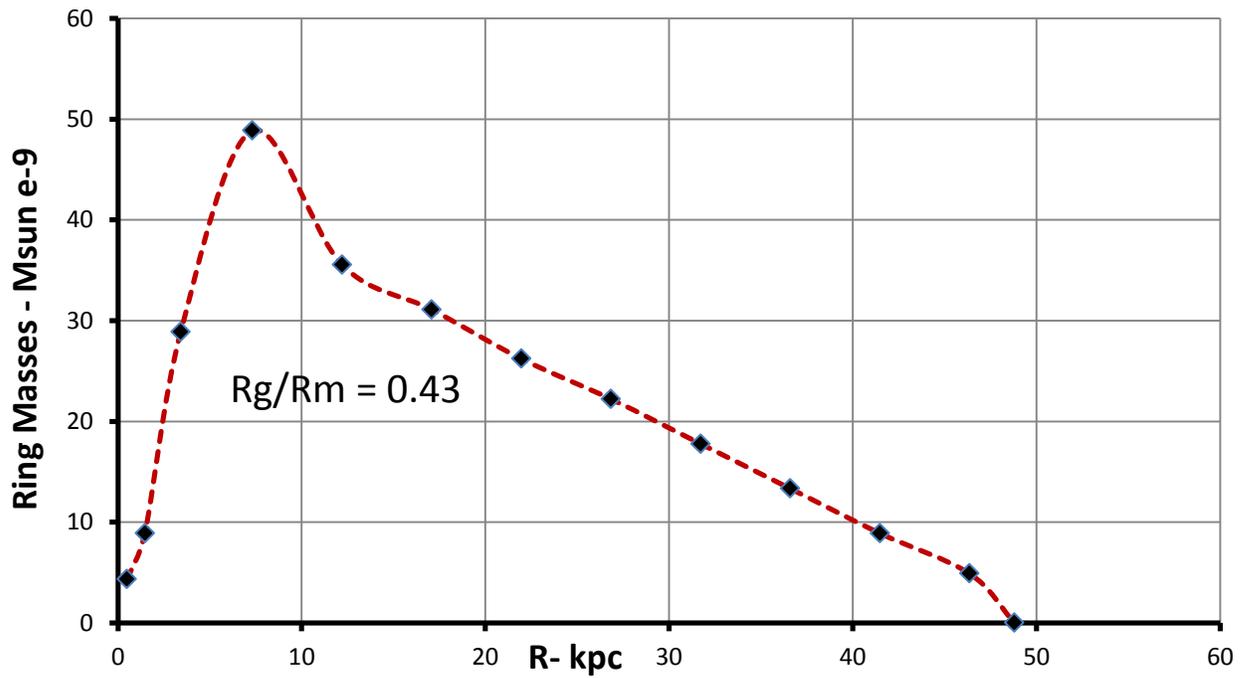Mm = 24.4 x 10e10 Msun
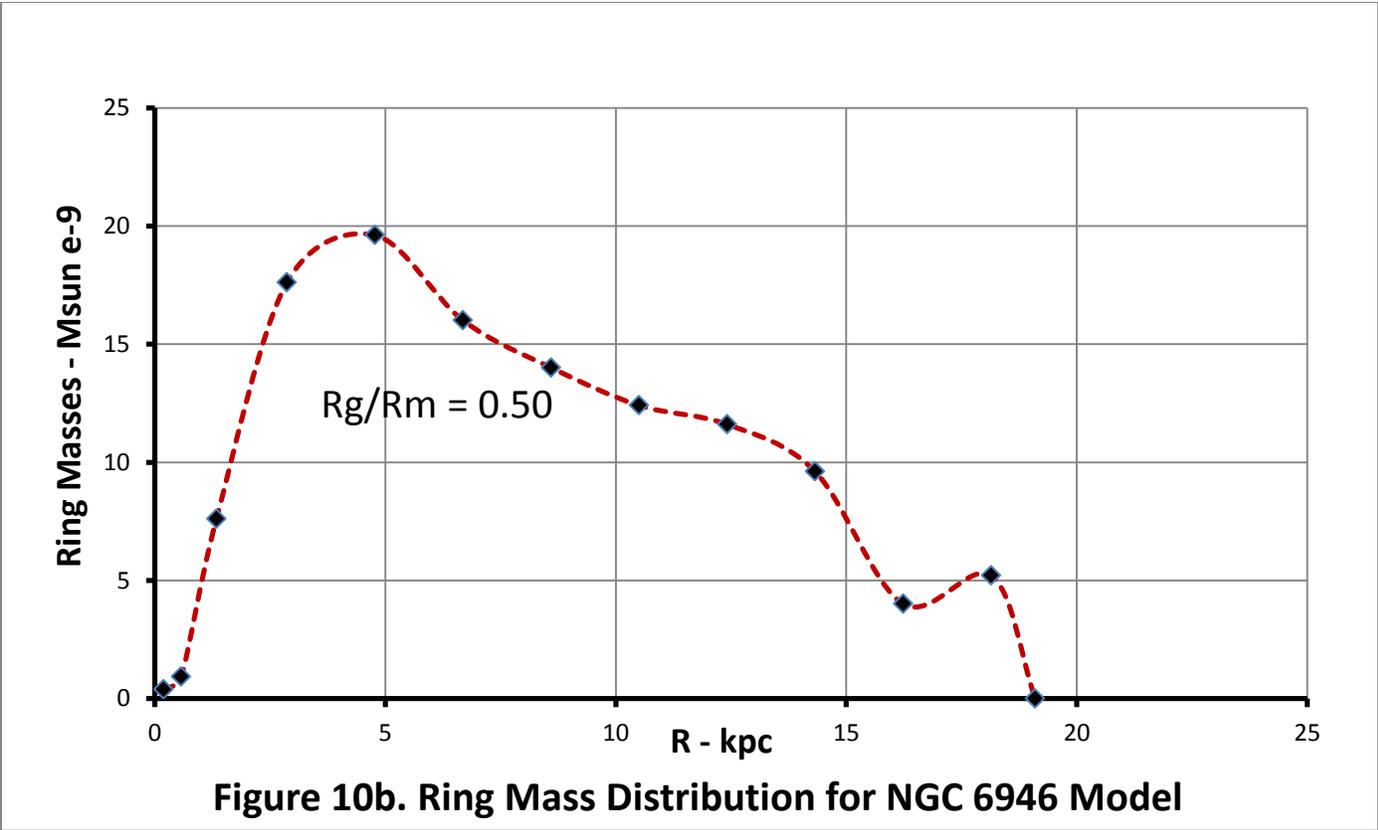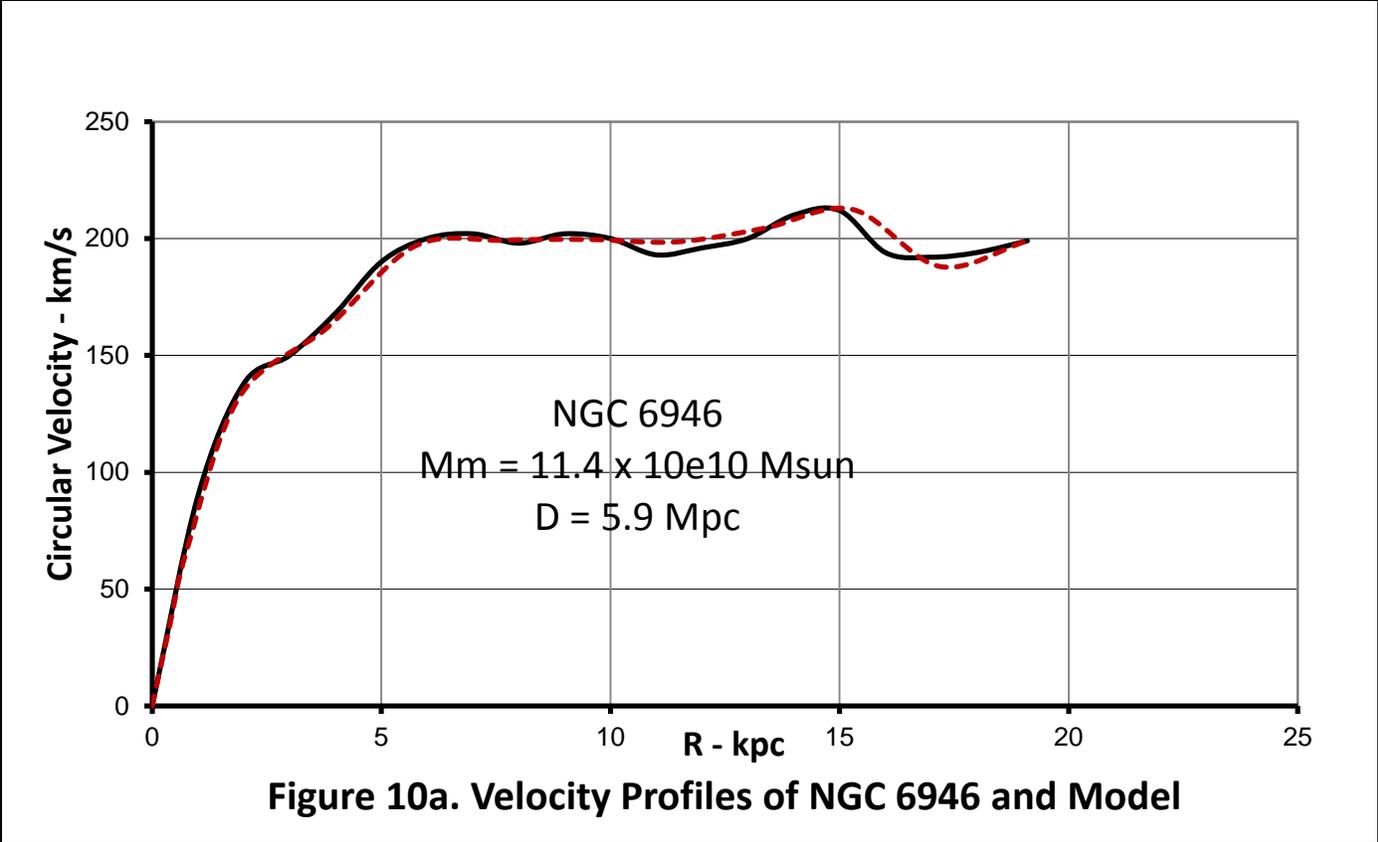D = 10.1 Mpc

Rg/Rm = 0.43

Figure 9b. Ring Mass Distribution for NGC 5055 Model

Figure 10a. Velocity Profiles of NGC 6946 and Model

NGC 6946
Mm = 11.4 x 10e10 Msun
D = 5.9 Mpc

Figure 10b. Ring Mass Distribution for NGC 6946 Model

Rg/Rm = 0.50
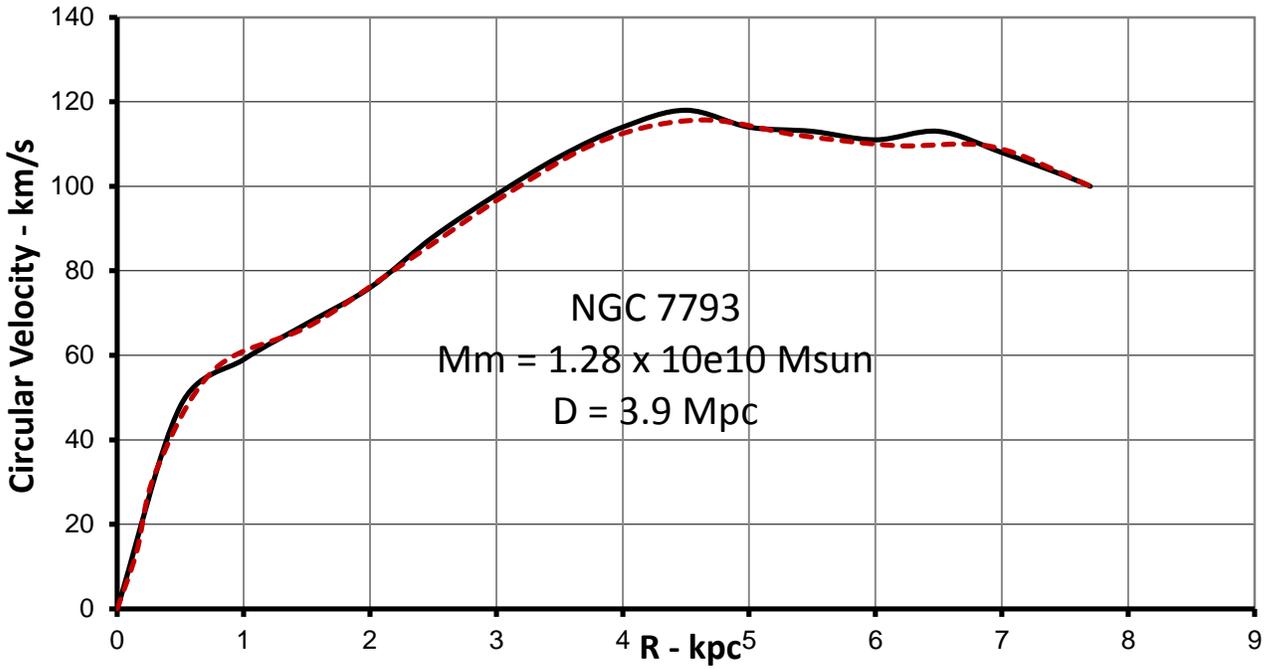
Figure 11a. Velocity Profiles for NGC 7793 and Model

NGC 7793
Mm = 1.28 x 10e10 Msun
D = 3.9 Mpc

Rg/Rm = 0.48
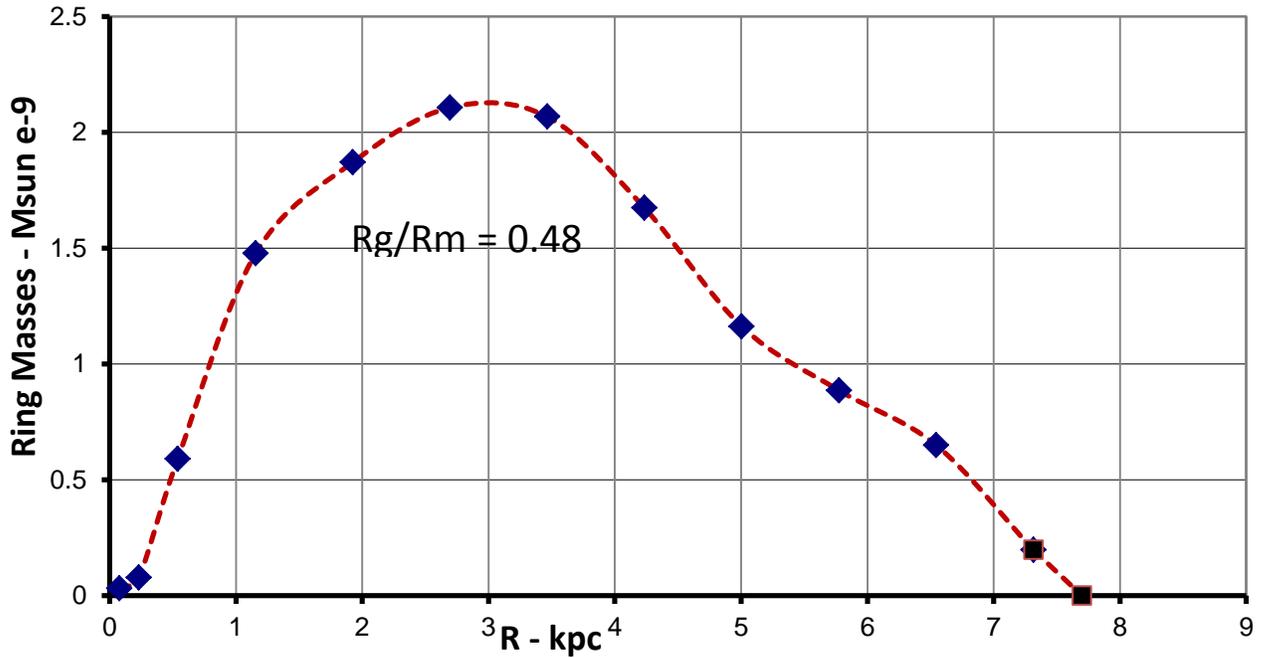
Figure 11b. Ring Mass Distribution for NGC 7793 Model

Figure 12. Velocity Profile for NGC 3198 Model
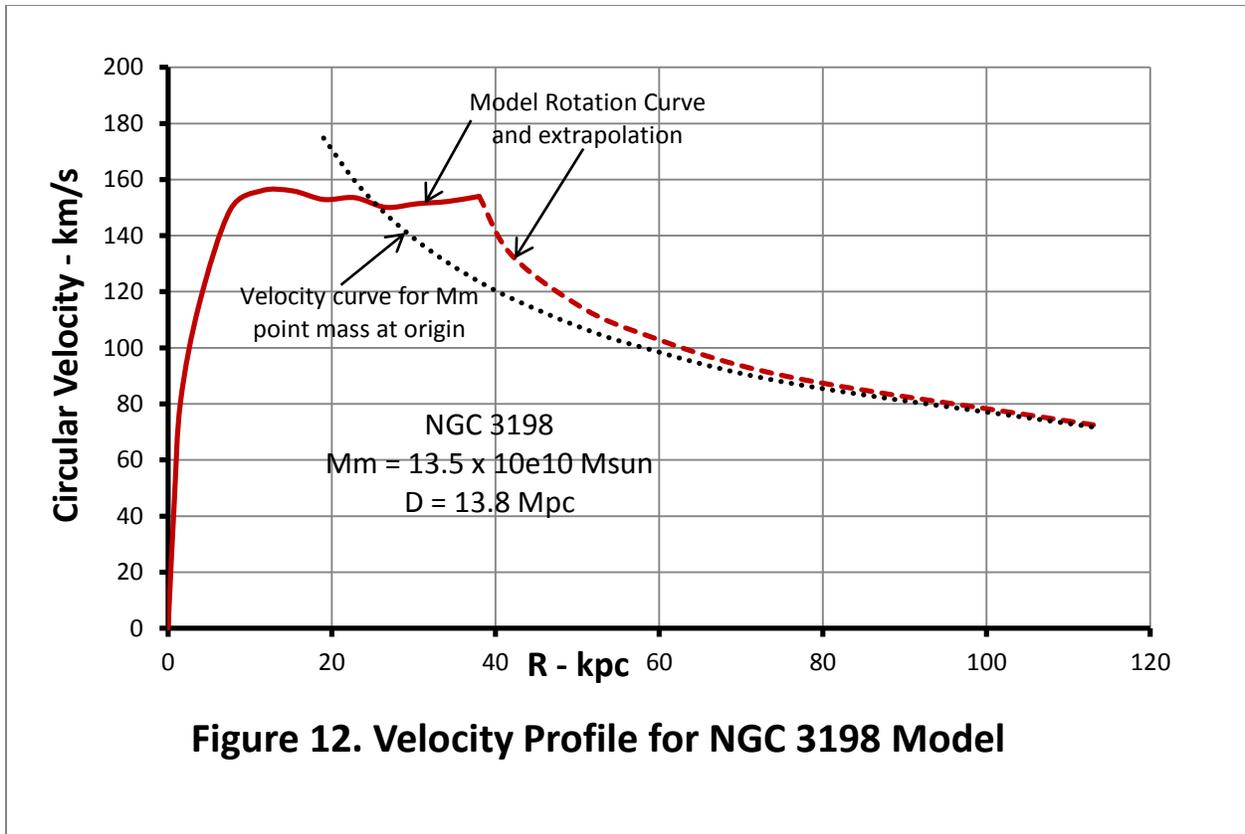
NGC 3198 (Figure 5a,5b) is often noted as the prototypical "flat" rotation curve galaxy, and has been extensively studied by professional astronomers. (e.g. References 3,4).   One of the advantages of the Newtonian model is that the gravitational force in the galaxy disk plane can be calculated beyond the outer edge of the disk, Rm. This allows appropriate extrapolation of the model velocity curve as shown in the dashed-red line in Figure 12. This would be the velocity of a satellite in a circular orbit in the galaxy disk plane. Also shown in Figure 12 is the (black-dot) Keplerian circular velocity, which assumes the galaxy mass (Mm) is concentrated at the disk center.   It can be seen that the model extrapolation curve and the Keplerian curve effectively merge at about 80 kpc (i.e. about 2 Rm, and this would be typical for "flat" rotation curves.)

NGC 3198 is an Sc type spiral galaxy with no noticeable nuclear bulge, so the three components of galaxy mass are stellar disc, HI gas and Dark Matter. Figure 13 displays the mass distribution of the stellar disc and Dark Matter components. (The HI gas component, which is typically a small percentage of the galaxy mass, is

ignored in this comparison.) The stellar component is modeled with a thin exponential disc that fits the luminosity profile as described in Reference 3. The Dark Matter component is determined by subtracting the stellar component from the total galaxy mass distribution. The model assumes that all of the galaxy mass is contained as a "flattened" mass within the disc limit of Rm. (Reference 5 (Jalocha et al, 2011) examines the vertical gradients of azimuthal velocity in a series of spiral galaxies, and concludes that the mass distribution appears to be dominated by a "flattened disc"-like component, rather than by a spheroidal dark-matter halo.)

Figure 13. Ring Mass Distribution of NGC 3198 Model and Stellar and Dark Matter Components
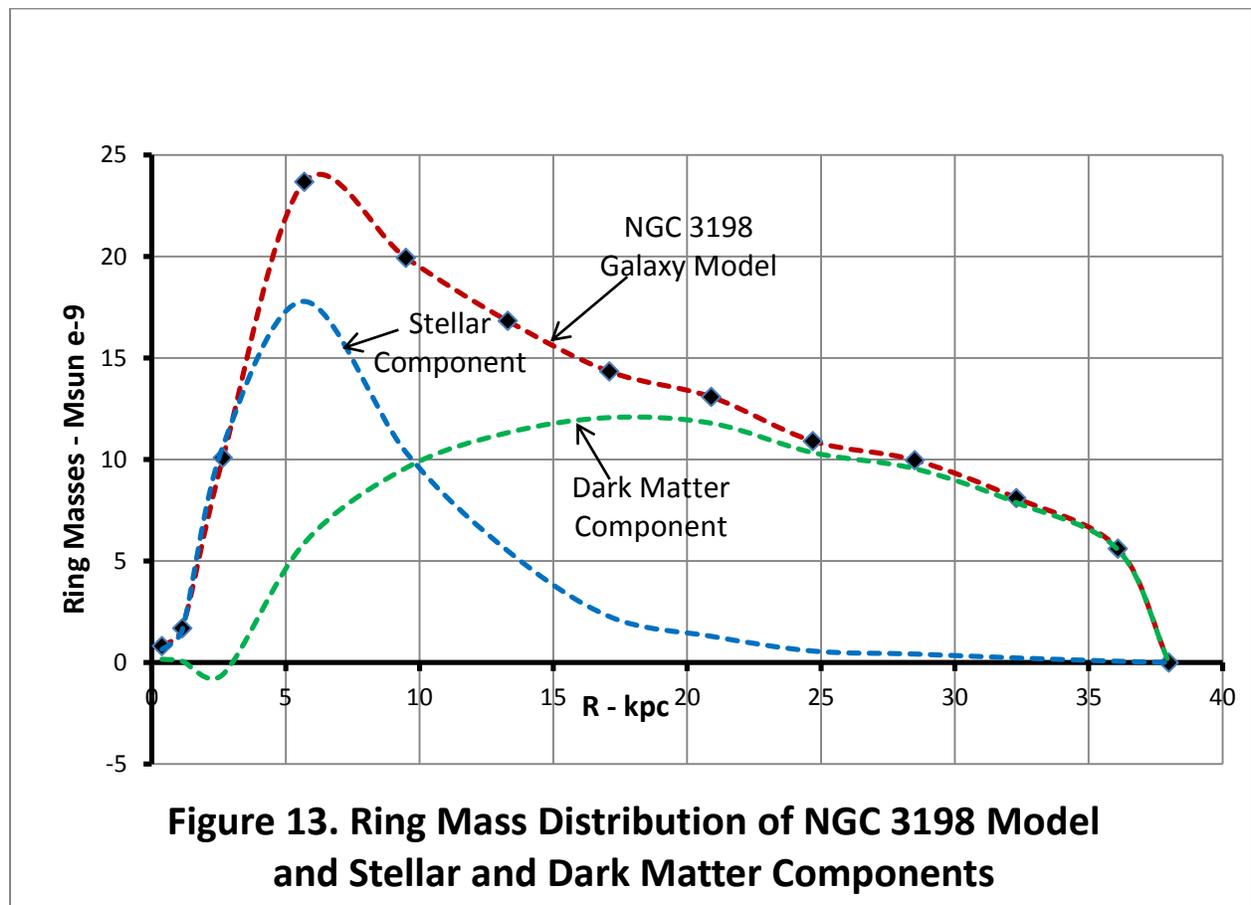
Summary

The Newtonian model of Reference 2 has been useful in estimating the enclosed galaxy mass and describing the mass distribution of 11 spiral galaxies, using the

rotation curves from THINGS (Reference 1.) The NGC 3198 model also demonstrated the extrapolation of the rotation curve beyond Rm, and indicated the mass distribution of the stellar and dark-matter components.

References

1. *High-Resolution Rotation Curves and Galaxy Mass Models from THINGS.*
    W.J.G. de Blok et al, October 2008   arXiv:0810.2100v2
2. *A Newtonian Model for Spiral Galaxy Rotation Curves.*
    Geoffrey M. Williams, April 2011   www.vixra.org/pdf/1104.0003v2.pdf
3. *Distribution of Dark matter in the Spiral Galaxy NGC 3198.*
    T.S. van Albada et al, February 1985   Astrophysical Journal, **295,** 305-313
4. *On the Apparent Coupling of Neutral Hydrogen and Dark Matter in Spiral Galaxies.*   H. Hoekstra, T.S. van Albada and R. Sancisi
    Mon. Not. R. Astron. Sci. **323**, 453-459 (2001)
5. *Vertical Gradients of Azimuthal Velocity in a Global Thin Disk Model of Spiral Galaxies NGC 2403, NGC 4559, NGC 4302 and NGC 5775.*
    Joanna Jalocha, Lukasz Bratek, Marek Kutschera, Piotr Skindzier
    arXiv:1006.2060v2 (astro-ph) April 2011