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Internal Dynamics of Local Group Galaxies

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Abstract. This talk reviews the internal dynamics of some of the different classes of Local Group galaxies. These include the dwarf spheroidal galaxies, the pure disk galaxy M33, the LMC and M31. The talk concludes with some general remarks about bulges and halos.

1. Introduction

The Local Group provides us with some very nearby examples of a rich variety of dynamical situations.

- M31 and the Milky Way: two large spirals, one with a small bulge and one with a large bulge.
- M33: an almost pure disk galaxy.
- the LMC and NGC 55: classic Magellanic spirals.
- a continuum of dwarf galaxies covering the whole range of star formation histories: these are excellent dark matter laboratories.

It is up to us to ask the right questions; this is not so easy. I will start with the dwarf spheroidal galaxies, then M33, then the LMC and Magellanic systems, and end with M31 and some discussion of bulges and halos.

2. The Dwarf Spheroidal Galaxies

There is some level of chance in whether we call a dwarf galaxy a dSph or a dIrr. The episodic star formation seen in many of the dSph galaxies (see Grebel's review paper in this volume) indicates that even at relatively recent times some of them would have looked more like dIrr systems. The Smecker-Hane et al. and Grebel & Stetson posters here show how Fornax had its last episode of star formation only about 10^8 years ago. Since most dIrr galaxies of similar luminosity are rotating, this makes it all the more puzzling why the Fornax dSph galaxy shows so little rotation (Mateo et al. 1991).

Velocity dispersions have now been measured for all of the dwarf spheroidal galaxies in the halo of the Milky Way (see Mateo 1998). For several, the samples of stars are large and it is clear that the effect of binary stars on the apparent velocity dispersion is not significant. The measured velocity dispersions are all larger than 6.5 $\mathrm{km\,s^{-1}}$. Masses and mass-to-light (M/L) ratios are usually estimated by fitting King models to derive central M/L ratios and total M/L ratios, assuming that the velocity dispersion σ is isotropic and that mass follows light. Several of the dSph galaxies are strongly dark matter dominated, with M/L ratios up to ~ 100 (e.g. Mateo 1998).

Does the mass follow the light in these systems? If the radial cutoffs seen in their star count distributions are tidal (as they are for globular clusters), then we might expect the dark matter also to be tidally truncated, and the velocity dispersion should then decrease with radius. But the shape of $\sigma(R)$ observed for Fornax and for Draco and UMi is flat (see Da Costa 1998), unlike that expected for a tidally truncated system. It is curious that this discrepancy is most striking for Fornax, which is among the *least* dark matter dominated.

The M/L ratio of the dSph galaxies increases with decreasing luminosity (Mateo 1998), following the relation $M/L = 2.5 + 10^7/(L/L_\odot)$. For the brighter systems, $M/L \downarrow 2.5$ (typical for a metal-poor old stellar population) as the dark matter becomes dynamically less significant.

For a set of well-determined dark halos in spirals, dIrr and dSph galaxies, Kormendy & Freeman (1999) find that the central density ρ_o of the dark halos increases by 3 dex from $M_B = -22$ to $M_B = -8$. For the faintest dSph galaxies, $\rho_\mathrm{o} \approx 1\ \mathrm{M_\odot\ pc^{-3}}$. Compare this with the density of the galactic disk near the sun, at about $0.1\ \mathrm{M_\odot\ pc^{-3}}$.

These very high densities of the dark halos of the smallest galaxies contrast with their very low stellar densities. If this is all correct, then it means that the very dense and very small dSph companions of the Galaxy have better prospects of surviving accretion by the Galaxy than do larger systems like the Sgr dwarf. Their high densities may reflect the density of the Universe at the redshift when these small objects formed.

3. M33

M33 is the nearest SA spiral with an almost pure exponential disk. Its absolute magnitude $M_V = -18.9$, and it has a very small bulge ($M_V > -15$) and a young blue nucleus ($M_V \approx -10.8$). The scale length of its disk depends on the tracer: 1.5 kpc in H, 1.8 kpc in B and 2.3 kpc as defined by the associations. This change of scale length with tracer is normal, and probably reflects a combination of internal extinction and the distribution of star formation. Many years ago, Walker (1964) nicely isolated the underlying stellar disk in M33, using photographic O (blue) and U (red) emulsions. Photographically differencing the U and O images leaves an almost amorphous underlying disk and weak bulge.

3.1. The Dark Halo of M33

M33 is much more extended in H I than in light: its optical diameter $D(\mu_B = 26.5) = 18$ kpc and its H I diameter $D(N_{H\,\mathrm{I}} = 2 \times 10^{19}\ \mathrm{cm^{-2}}) = 36$ kpc. Its H I distribution shows a sharp radial cutoff (Corbelli et al. 1989): $N_{H\,\mathrm{I}}$ drops by 1 dex $\mathrm{kpc^{-1}}$ at large radius, which is probably due to ionization by galactic or maybe metagalactic UV radiation. If this is correct, then we would expect faint (but now detectable) Hα emission beyond the apparent H I cutoff.

From the H I kinematics, it is already clear that M33 has a massive dark halo. The new extended Hα data (Bland-Hawthorn et al. 1998) reaches out to a radius of 25 kpc and makes it even clearer. The rotation curve continues to rise gently to the edge of the Hα detection. Out to this limit:

- the luminous mass to dark mass ratio = 1/15 (comparable to the Milky Way),
- the total mass is $1.1 \times 10^{11} M_\odot$,
- the luminosity $L_V = 3 \times 10^9 L_{V,\odot}$, and
- the enclosed mass to light ratio $M/L_V > 35$.

3.2. The Luminous Halo of M33

Photometry of a field at a radius of 7 kpc (Mould & Kristian 1986) shows that M33 has a metal-poor stellar halo, although its bulge is very small. This indicates again that bulges and metal-poor halos are not strongly related. The cluster population of M33 contains young clusters and old clusters, as in the LMC (see van den Bergh, 1991). There is, however, not such a clear segregation in age (color) between the young and old clusters in M33 as there is in the LMC. Also, the young blue clusters in M33 are mostly less luminous than those in the LMC, indicating a more quiescent history.

The young clusters in M33 move with the H I (velocity dispersion ≈ 15 km s^{-1}), as do the young clusters in the LMC. The older clusters in M33 are metal-poor (Sarajedini et al. 1998) but apparently younger (ages ≈ 10 Gyr) than the old clusters in the Milky Way. The difference between the kinematics of the old M33 clusters and the old LMC clusters is particularly striking:

- in M33, the older clusters have a velocity dispersion $\sigma \approx 70$ km s^{-1}. If the halo has a similar $\rho \propto r^{-3.5}$ density distribution to the halo of the Milky Way, then from the rotation curve of M33 we would expect $\sigma \approx 75$ km s^{-1}. The M33 clusters show no significant rotation.
- in the LMC, the old clusters are part of the rotating old disk, with $\sigma \approx 23$ km s^{-1} (see Schommer 1993).

We conclude that the halo of M33, as defined by its old clusters, is qualitatively similar to the metal-poor halos of the Milky Way and M31. The LMC is the unusual system.

4. The LMC

In this section, I will discuss briefly the underlying nature of Magellanic systems, the rotation of the LMC, its globular clusters and RR Lyrae stars and the question of whether the LMC has an old halo, and finally some new results from the HIPASS survey about the tidal leading arm of the Magellanic Stream.

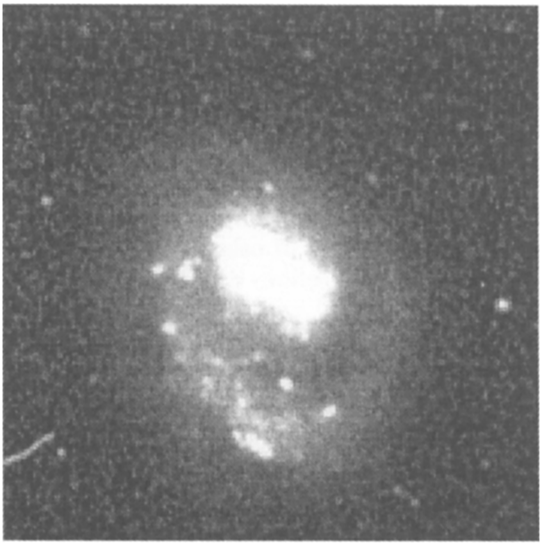

Figure 1. The Magellanic system NGC 4618 (Digital Sky Survey). Note the off-center bar and the asymmetric major arm.

4.1. The Underlying Nature of Magellanic Systems

Deep images of Magellanic systems, such as the LMC and NGC 4618 (see Fig. 1), show the disk, the off-center bar and the asymmetric spiral structure which are their defining characteristics.

Although these systems are fairly common and one of them is our nearest major neighbour, not much dynamical work has been done on these systems so far: their double asymmetry (the bar and its off-center location) makes them dynamically difficult. Colin & Athanassoula (1989) studied the response of gas to a steady-state doubly asymmetric potential and were able to reproduce the asymmetric major spiral arm which is commonly seen in the Magellanic systems (see also Gardiner et al. 1998).

The bars of SB galaxies are believed to form through the instability of their rotating disks. The formation of this relatively common double asymmetry is not yet understood. At this stage, we do not know whether their structure is transient or quasi-steady. We note that Magellanic systems often occur in pairs (e.g. LMC and SMC) but not always. They are usually gas-rich, and can be as bright as $M_V \approx -18.5$.

4.2. The Rotation of the LMC

The internal motions in the LMC are primarily rotation, but the rotation field is not simple and undisturbed. A new H I mosaic survey with the ATCA (Kim et al. 1998) shows the overall rotation pattern clearly. A tilted ring analysis of the H I velocity field shows a strong radial change in the position angle of the kinematic line of nodes.

Kunkel et al. (1997) studied the kinematics of the carbon stars in the outer regions of the LMC and found that the velocity dispersion stays roughly constant with radius at about 15 $\mathrm{km\,s^{-1}}$ over the radius interval 3 to 6 kpc. For a classical disk with constant vertical scaleheight, we would expect the velocity dispersion to fall with radius, so this observation suggests that the outer disk may be significantly flared (Alves et al. 1998). Alternatively, if the stellar disk also has a twist in its kinematic line of nodes, this could contribute to the apparent constancy of the velocity dispersion derived by Kunkel et al..

Kim et al. generated a composite rotation curve, using their H I data in the inner 3 kpc and the carbon star data in the outer regions. The rotation curve shows a large dip between 3 and 4 kpc in radius, and the usual rotation curve analysis (i.e. stellar disk + gas + dark halo) does not provide a convincing representation of the combined data. The rotation field is clearly complex and disturbed.

4.3. The Globular Clusters and RR Lyrae Stars of the LMC

Here is a summary of the situation for potential halo tracers in the LMC.

- The young clusters move with the H I; their velocity dispersion is about 17 $\mathrm{km\,s^{-1}}$.

- Unlike the situation in M33, the old clusters also appear to be part of the rotating disk (Freeman et al. 1983, Schommer et al. 1992). Their velocity dispersion is about 23 $\mathrm{km\,s^{-1}}$. For a non-rotating halo population in the LMC, we would expect a velocity dispersion of about 50 $\mathrm{km\,s^{-1}}$. So the clusters provide no evidence for the presence of a kinematic halo as in the Milky Way, M31 and M33.

- The RR Lyrae stars are another potential halo tracer in the LMC, but as yet there is little data on their kinematics. Their distribution on the sky gives a clue to their true spatial distribution. Alves (1998) derived the surface number density distribution of RR Lyrae stars in the LMC, using a large sample from the MACHO survey and some outer fields from Kinman et al. (1991). The RR Lyrae star distribution is exponential, with a scale length of 1.6 ± 0.1 kpc, which is similar to the 1.5 kpc scale length for the photometric surface brightness distribution of the disk of the LMC (de Vaucouleurs 1957, Bothun & Thompson 1988). The similarity of the two scale lengths suggests that the RR lyrae stars of the LMC are probably disk objects, like the old clusters, and supports the view that the LMC may not have a metal-poor halo.

4.4. HIPASS and the Magellanic Stream

The origin of the Magellanic Stream remains contentious: is it due to tidal interactions or to ram pressure stripping of gas from the Magellanic system by the corona of our Galaxy? The tidal simulations predict a leading couterpart to the Magellanic Stream (e.g. Gardiner & Noguchi 1996) which had not previously been detected. Putman et al. (1998) have made a preliminary H I map of the entire sky south of declination −60° from part of the H I Parkes All Sky Survey (HIPASS) data and have clearly detected this leading arm which persists over several velocity channels. This supports the tidal picture for the origin of the Magellanic Stream.

5. M31

5.1. The Structure of the Luminous Halo of M31

Surface photometry and star counts by Pritchet & van den Bergh (1994) show that the surface brightness distribution along the minor axis of the bulge/halo of M31 follows an $r^{1/4}$ law very closely from $r = 200$ pc to $r > 20$ kpc: at this radius the surface brightness $\mu_V \approx 30$ mag arcsec^{-2}. The effective radius along the minor axis is about 1.3 kpc. Expressed as a power law, the inferred luminous density follows $\rho_L \sim r^{-4}$ to r^{-5} in the outer regions. There is an indication that the halo is fairly flat, with an axial ratio of about 0.55 at $\mu_V = 28$.

For comparison, our Galaxy has a smaller boxy bulge with a near-exponential light distribution on the minor axis. This is common for small bulges (Courteau et al. 1996). The outer halo of the Galaxy follows the luminous density distribution $\rho_L \sim r^{-3.5}$.

5.2. The Dark Halo of M31

Kent's (1987) decomposition of the rotation curve of M31 gives the following parameters (values for the Galaxy in the third column):

Disk mass	$15 \times 10^{10}\ M_\odot$	$11 \times 10^{10}\ M_\odot$
Bulge mass	3.6×10^{10}	2×10^{10}
Mass($r < 30$ kpc)	37×10^{10}	30×10^{10}
Rotational velocity	240 km s^{-1}	220 km s^{-1}

M31 is slightly more massive than the Galaxy and has a larger bulge/disk ratio. The mass of M31 within $r = 30$ kpc can also be estimated from the kinematics of its globular clusters: this procedure requires assumptions about the orbital properties of the cluster system. Huchra et al. (1991) derive $(31 \pm 5) \times 10^{10}\ M_\odot$ from 150 clusters with a velocity dispersion of 155 km s^{-1}, and Federici et al. (1993) find $(50 \text{ to } 80) \times 10^{10}\ M_\odot$ from 176 clusters. These estimates are in fair agreement with the rotation curve value.

Timing arguments give an estimate of the total masses of M31 and the Galaxy. M31 has a galactocentric radial velocity of -118 km s^{-1}. If the initial separation is small, then adopting an age for the Universe gives the total mass of (M31 + the Galaxy). The simplest estimates assume radial orbits, and give a lower limit on the total mass. For an adopted distance of 710 kpc, and an age of 18 Gyr, the total mass is $40 \times 10^{11} M_\odot$. Distributing this total between the two galaxies according to the Fisher-Tully relation gives

Mass of Galaxy	$16 \times 10^{11} M_\odot$
Mass of M31	$24 \times 10^{11} M_\odot$

For M31 and the Galaxy, this is consistent with flat rotation curves with the rotational velocities given above, extending out to a radius of about 150 kpc in each galaxy. The enclosed masses within R kpc are then

$$M_G(R) = 1.1R \times 10^{10} M_\odot$$

$$M_{M31}(R) = 1.4R \times 10^{10} M_\odot$$

More detailed studies (e.g. Raychaudhury & Lynden-Bell 1989; Schmoldt & Saha 1998) give similar estimates for the total mass. Kroeker & Carlberg (1991) made timing-style estimates of masses for binary galaxies identified in CDM simulations, and found that the simple timing estimates typically underestimate the total masses by a factor of about 1.7.

5.3. The Halo Globular Clusters of M31

The halo clusters of M31 are similar to those of the Galaxy in many ways:

- the M/L ratio
- their stellar population at a given [Fe/H]
- the scaling laws between core radii, luminosity and surface brightness
- the radial distribution of clusters within the parent galaxy (density $\sim r^{-3}$)
- orbital parameters of the clusters in the parent galaxy (Cohen & Freeman 1991)
- specific frequency S (i.e. the number of clusters per $M_V = -15$ unit of luminosity of the parent spheroid). The table below gives the number of clusters, the absolute magnitude of the spheroid, and the specific frequency for the Galaxy and for M31 (de Vaucouleurs 1993):

	N	M_V(spheroid)	S
Galaxy	162 ± 15	-18.8 ± 0.2	4.9 ± 0.8
M31	700 ± 10	-20.4 ± 0.2	4.7 ± 1.0

  These numbers are comparable to those for normal ellipticals.

- luminosity functions of the two families of clusters.

(see Freeman 1998 for further references). This all indicates fairly similar formation conditions and formation processes, and similar evolution of the cluster populations in the two galaxies.

The M31 globular clusters overall show a similar range of [Fe/H] to the Milky Way globular clusters (Huchra et al. 1991). For the halo clusters in particular (i.e. clusters in the Galaxy that are more than 4 kpc from the center, and clusters in M31 which lie outside the projected disk), the M31 clusters are marginally more metal-rich (Reed et al. 1994). As a function of projected radius, the M31 clusters show at most a weak metallicity gradient (Huchra et al. 1991).

The kinematics of the globular clusters in M31 and in the Galaxy are again qualitatively similar. The more metal-rich clusters in M31 ([Fe/H] > -0.8) show clear systemic rotation out to a radius of at least 10 kpc (Huchra et al. 1991), while the metal-poor clusters have little systemic rotation.

5.4. The M31 Halo Field

Although the halo globular clusters of M31 and the Galaxy are similar in many aspects, this is certainly not the case for the halo field stars in these two systems. Deep color-magnitude diagrams in several halo fields in M31, at radial distances from about 7 to 40 kpc, show that the halo field stars cover a very wide range of metallicity, from about -2.4 to $+0.2$. Their metallicity distribution is peaked at $[\mathrm{Fe/H}] \approx -0.6$, which is much more metal-rich than the peak for the globular clusters in M31 and the Galaxy, and much more metal-rich than the peak for the halo field star distribution in the Galaxy. The M31 halo stars and the galactic halo stars have very different metallicity distributions. See Durrell et al. (1994) for a clear demonstration of these differences.

6. Bulges and Halos

We have seen some striking similarities and differences between the dynamical and chemical properties of M31 and the Galaxy. I will try to discuss what these might mean for understanding galaxy formation. First I will summarise again some of the properties of the M31 bulge.

6.1. The Bulge of M31

- M31 has a *real* $r^{1/4}$ bulge from 200 pc to 20 kpc
- the chemical properties of the outer bulge or halo of M31 are very different from the halo of our Galaxy
  - the mean metallicity is about -0.6, much higher than for the halo of the Milky Way
  - the globular clusters are systematically more metal-poor than the field stars, as in many giant ellipticals but unlike our Galaxy

I suspect that the prominent, more metal-rich bulge dominates the metal-poor population in M31 at all radii, as it does in giant ellipticals.

6.2. Structural and Chemical Properties of Large Bulges

- the $r^{1/4}$ light distribution is the norm for large bulges, as in M31 and the Sombrero galaxy.
- the $r^{1/4}$ structure, as in giant ellipticals, is usually associated with a fairly violent merger/aggregation history.
- the bulges of spirals show the (Mg/Fe - absolute magnitude) relation in the same sense as for giant ellipticals (higher Mg/Fe for brighter galaxies). The usual interpretation is that SN-driven winds act in the more luminous systems to remove the gas quickly after the early star formation and so reduce the iron enrichment by the slower-onset SN I.

- if this is all correct, then it suggests that the formation of *large* bulges was quick, dynamically and in their star formation history, as for giant ellipticals[1].

- if the globular clusters formed together with the bulge in M31, then this rapid formation would indicate a small range of age among the clusters. Then the clusters should show no second parameter effect (as observed), if age is the second parameter.

6.3. Our Halo and Other Bulges

Although we do not yet know much about the kinematics of the outer bulge of M31, studies of planetary nebulae in the outer parts of the bulge of the Sombrero galaxy show fairly rapid rotation (Freeman et al. 1999). For giant ellipticals, which are mostly slow rotators in their inner regions, the planetary nebulae again show that there is a substantial amount of angular momentum in their outer regions (Arnaboldi et al. 1994 for NGC 1399; Arnaboldi et al. 1998 for NGC 1316; Hui et al. 1995 for Cen A). There seems to be a clear distinction between the angular momentum content of the halo of (i) our Galaxy (near-zero or maybe even in the opposite sense to the angular momentum of the disk: see Freeman 1996 for references) and (ii) the outer bulge of the Sombrero galaxy or the outermost regions of giant elliptical galaxies.

Simulations of hierarchical aggregation show angular momentum migrating outwards via the transient torques associated with the interactions. The least bound parts of the aggregating system acquire angular momentum at the expense of the most bound (Frenk, 1987; Zurek et al. 1988). I suspect the critical difference between halos (as in our Galaxy) and outer bulges (as in the Sombrero and probably M31) is whether:

1. star formation in the halo/outer bulge occurred *together* with the aggregation of the dark corona (so redistribution of angular momentum in the aggregation process affected the stellar halo), or

2. the halo formed *later* by accretion, so was not affected by the angular momentum redistribution.

I would predict that the relatively metal-rich $r^{1/4}$ bulge of M31 rotates fairly rapidly ($\sim 100\ \mathrm{km\,s^{-1}}$) at 10 to 20 kpc from the center. The kinematics of the outer bulge of M31 will soon be known from planetary nebulae (Ford et al. 1999) and from the red giants (see Reitzel & Guhathakurta 1998).

6.4. Globular Cluster Formation

While speculating about the importance of star formation in the aggregation phase, I would like to close with a comment about globular cluster formation. The elliptical galaxies give an important clue.

- Most ellipticals have specific frequencies (see §5.3) $S \approx 5$, but some have $S \approx 15$.

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[1] Sil'chenko cautions that some of the Mg/Fe enhancement in large bulges may be associated with chemically distinct nuclei rather than with the bulge itself: see the discussion

- The distribution of metallicity among the globular clusters is often *bimodal.*
- In clusters with large values of S, the excess clusters lie in the *metal-poor* mode (Forbes et al. 1997). This important result means that major mergers of evolved spirals are unlikely to produce the excess clusters, as has sometimes been argued.
- But there seems no doubt that the merger environment is ideal for forming globular clusters: we do see large numbers of globular clusters forming in present day gas-rich mergers (e.g. NGC 4038/4039: Whitmore & Schweizer, 1995).

This all suggests that the likely phase for globular cluster formation is during the active aggregation phase, when the galaxy is coming together in its first $\sim$ Gyr and there is much merging of gas-rich fragments.

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Discussion

Zaritsky: How do limits on the binarity from the radial velocity monitoring in the dSphs compare with the binarities inferred from synthetic CMDs?

Armandroff: The two Galactic dwarf spheroidals with long-term radial velocity monitoring and subsequent binary frequency analysis are Draco and Ursa Minor. This analysis, by Olszewski, Pryor & Armandroff (1996, AJ, 111, 750), assumes a period distribution and secondary mass distribution from the solar neighborhood. The binary population used in the synthetic CMDs does not adopt the solar neighborhood distributions, so it is complicated to compare the inferred and assumed binary populations.

Sil'chenko: In the bulge of M31 the magnesium-to-iron ratio is twice solar, that is true. But for other large bulges the situation may be different. Up to now there are no large data sets for bulges outside nuclei for galaxies more distant than M31. So now the situation with magnesium-to-iron ratio in the bulges of early-type spirals is still uncertain.

Freeman: This is important: we need to know how the Mg/Fe ratio changes with luminosity for the main body of the bulges.

Lynden-Bell: Could it be that, as Martin Weinberg was saying in Canberra for the Magellanic Clouds, the polarization of the Galaxy's halo by Fornax can extend its effective potential well?

Freeman: Yes, it would be interesting now to quantify this for the Fornax potential well.

Filipovic: In about 1 year's time, we will have an H I narrow-band multi-beam survey of the Magellanic system which will significantly improve on the present Parkes multi-beam survey. Also, ATCA H I observations of the Magellanic bridge are in progress and even at this stage show interesting features such as the "Lagrangian point".

Maeder: You mentioned that the contribution from dark matter does not seem to be truncated by the tidal interactions in the outer part of dwarf galaxies. What kind of inference can be drawn from this finding concerning the physical properties of dark matter? Should dark matter not, if cold, be subject to the same gravitational interaction as the stars?

Freeman: I agree - in basic tidal dynamics, the dark matter and stars should suffer similar truncation. Maybe the dynamical situation is more complicated - for example, perhaps the truncation of the luminous matter is not tidal at all.