WHERE DOES THE GALAXY END?

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Abstract.

The spatial distribution of the outlying satellites of the Galaxy has been determined by fitting a three dimensional surface to the positions of 10 companion galaxies and 13 distant globular clusters. Both groups show a highly flattened distribution whose minor axes are aligned to within $\sim 5°$. The combined group of 23 objects shows a triaxial distribution with semimajor axis extending $\sim$ 400 kpc. The minor axis is inclined at $\sim 76°$ to the Galactic poles. There is a suggestion of a nested hierarchy consisting of satellite galaxies, globular clusters, and distant halo field stars, in order of decreasing spatial extension.

1. History and an Operational Definition of the Galaxy

The question posed in the title has an interesting history (*c.f.* Plaskett & Pearce 1935 for a review of early developments). Briefly, the first quantitative investigation of the Galaxy's extent was made near the end of the 18th century by W. Herschel who analyzed star counts as a function of magnitude in different areas of the sky. Herschel's Galaxy had the sun near the center of a flattened system whose major diameter, based on a modern calibration, was $\sim$ 2 kpc. Much later, Kapteyn (1922) also using the results of star counts arrived at a very similar picture (*i.e.* heliocentric, but whose size was now $\sim$ 17 kpc). Neither Herschel nor Kapteyn incorporated the distorting effects of interstellar absorption into their models. It was Shapley (1918) who used the distribution of globular clusters to define the picture of the Galaxy that we use today. The major result of Shapley's work was the demonstration that the sun was displaced from the center of

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the system by what we now believe to be ~ 8 kpc. Furthermore, the size of Shapley's Galaxy as delineated by the roughly spherical distribution of globular clusters was ~ 30-40 kpc.

For the purpose of this discussion we shall follow historical precedent and define the Galaxy to be the volume contained by the localized concentration of the most spatially extended light (baryonic) tracer. Such a definition is likely to result in a lower limit to the true extent of the Galaxy since the dominant component of the universe is currently believed to be non-baryonic and hence dark and dissipationless. As we discuss in the next section, the most spatially extended light tracers presently known are the satellite galaxies, and it is the spatial distribution of these objects which is the main focus of this contribution.

2. The Spatial Distribution of the Outlying Satellites

When Shapley presented his view of the Galaxy in 1918, most of the known globular clusters lay within ~ 20 kpc of the Galactic center. It was nearly twenty years later when Shapley discovered the first of the family of dwarf spheroidal galaxies. It was not until the early 1950's, that a number of new relatively distant, low surface brightness satellites of the Galaxy (both dwarf spheroidal galaxies and globular clusters) were discovered on plates taken with the newly commissioned 48-inch Schmidt telescope on Mt. Palomar. Since that time other low surface brightness satellites have been discovered, primarily in the southern hemisphere. A recent compilation of globular cluster distances by Tello (1994) shows 16 clusters with distance from the Galactic center (R_g) > 25 kpc while a similar compilation of local group galaxies by van den Bergh (1994) contains 11 galaxies with R_g < 400 kpc.

Kunkel & Demers (1976) and Lynden-Bell (1976) were the first to discuss the spatial distribution of these outlying systems. Kunkel & Demers and Kunkel (1979) drew attention to the fact that most of the outlying systems (those with R_g > 25 kpc) lay in a well defined plane. Lynden-Bell (1982), on the other hand, noted the tendency for certain objects (*i.e.* Ursa Minor, Draco, and Carina), to be coincident with the Magellanic Stream of neutral hydrogen. This, in turn, led him to the hypothesis that this planar system was composed of debris from a greater tidally-disrupted Magellanic galaxy. Furthermore, Lynden-Bell (1982) postulated that the tidal demise of a second (now possibly unrecognizable) 'victim' had given rise to objects defining the Fornax- Leo (I and II)-Sculptor (FLS) stream. More recently, Majewski (1994) has noted that the Phoenix and Sextans systems, as well as a number of globular clusters with the reddest horizontal branches, also populate the FLS stream and thus reinforce Lynden-Bell's hypothesis.

Inspired by this earlier work another approach has been taken here.

Rather than attempting to fit the satellites into great streams I have tried to fit a three dimensional surface to all of the outlying systems together. The surface was determined by doing a least squares solution for α, β, γ, δ, ϵ, and ϕ in the following expression:

$$\alpha x^2 + \beta y^2 + \gamma z^2 + 2\delta xy + 2\epsilon xz + 2\phi yz = 1 \quad (1)$$

where x,y,and z are rectangular Galactocentric coordinates. The cross terms in the above expression can be eliminated by rotating the coordinate system to one aligned with the principal axes x', y', z' to yield the equation for a triaxial ellipsoid:

$$\frac{x'^2}{a^2} + \frac{y'^2}{b^2} + \frac{z'^2}{c^2} = 1 \quad (2)$$

Using the above procedure a surface has been fit to a group of 23 objects: 13 globular clusters (the 16 clusters in Tello's list with $R_g > 25$ kpc minus NGC1466, NGC1841 and Recticulum which may be satellites of the LMC) and a group of 10 local group galaxies (the 11 galaxies with $R_g < 400$ kpc minus the SMC). The newly discovered dwarf spheroidal galaxy in Sagittarius (Ibata *et al.* 1994) was not included because its value of R_g appears to be less than 25 kpc. The results of the solution are shown in Fig. 1. Note that the surface is indeed triaxial with $c/a = 0.24$, $b/a = 0.52$ and that the direction of the minor axis points to $l = 306°$, $b = 14.5°$ (*i.e.* highly inclined to the Galactic pole). The uncertainties associated with each of the parameters in Fig. 1 are 90% confidence limits.

In view of these somewhat surprising results, which are based on such a small number of objects, some additional numerical experiments were carried out. The first test was to determine how often an *ellipsoidal* distribution with flattening $c/a \leq 0.24$ would occur by chance given an isotropic distribution (with allowance for the zone of avoidance) of 23 objects with the same radial distribution of distances as our sample. The result is 150 times out of 1000 trials. This ratio is reduced to 77 times out of 1000 if the additional constraint of $b/a \leq 0.52$ is also imposed. Next, having determined that the minor axis of the system of 13 globular clusters ($l = 307^{+17}_{-23}$, $b = 19.1^{+2.1}_{-21.4}$) was within $\sim 5°$ of the minor axis defined by the system of 10 satellite galaxies ($l = 305^{+39}_{-2.3}$, $b = 14.1^{+3.9}_{-6.6}$) from separate solutions of equations 1 and 2, it was found that such a situation would occur only 2 times in 1000 by chance, assuming once again an isotropic distribution of directions within each group of objects. To summarize, it is perhaps not surprising that 23 objects distributed isotropically would yield an ellipsoidal distribution as extreme as is observed in Fig. 1. It will happen by chance 8% of the time. What is much less likely to happen by chance is to have two *ellipsoidal* groups of objects with combined $c/a \leq 0.24$ whose minor axes

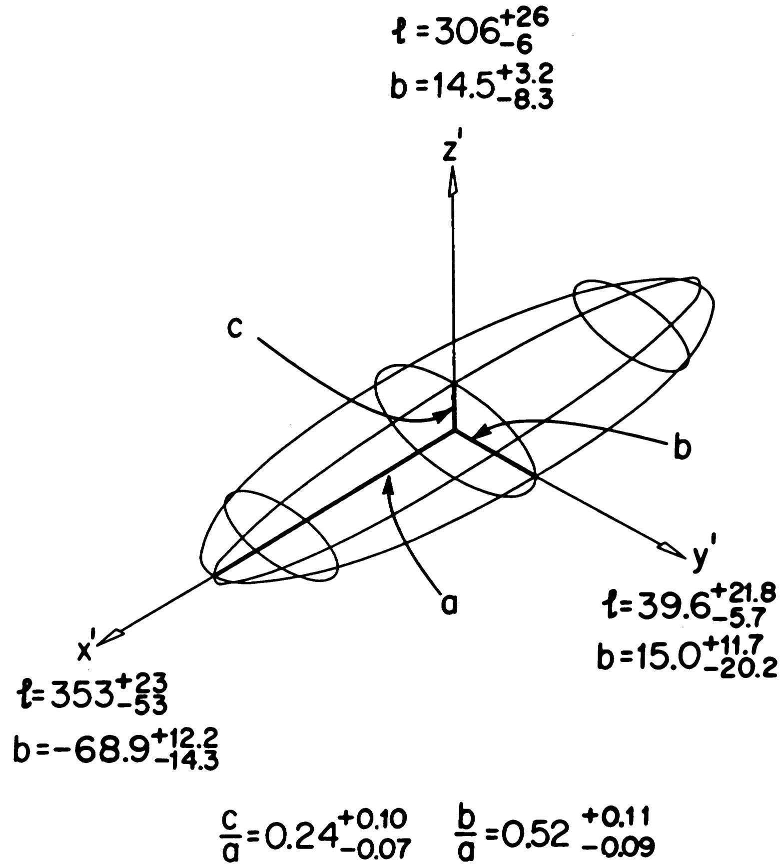

Figure 1. The orientation (in Galactic coordinates) and the shape of the surface defined by the distribution of 23 outer globular clusters and satellite galaxies.

are aligned to within 5°. The latter result appears to imply that there is a close connection between the globular clusters and the satellite galaxies.

Figure 2 shows the spatial distribution in rectangular coordinates of the 23 objects used in the solution in a coordinate system aligned with the principal axes of Fig. 1. Note that the major axis extends to nearly 800 kpc. Figure 3 shows the distribution of all of the local group galaxies in van den Bergh's (1994) compilation plotted in the same coordinate system but with reduced scale. Notice that the minor axis of the above ellipsoid points very nearly towards M31. Furthermore, there is a hint that the group of objects associated with M31 may be exhibiting a spatial distribution similar to the objects around the Galaxy. Figure 4 shows plots similar to Figs. 2 and 3 but with a projection perpendicular to the line of nodes, in order to show the effects of the zone of avoidance on the spatial distribution. If the

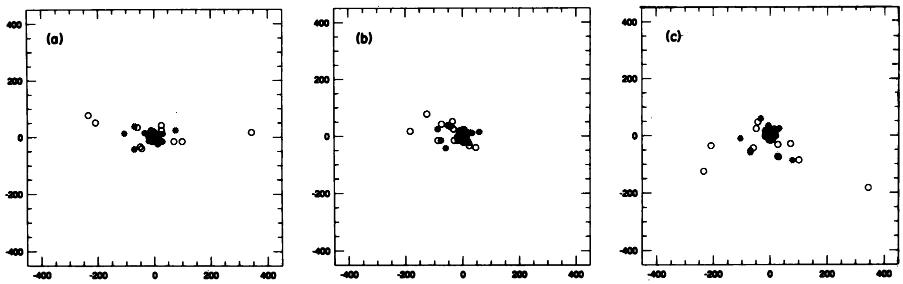

Figure 2. The spatial distribution of globular clusters (filled circles) and satellite galaxies (open circles) in the 'halo' coordinate system of Fig. 1. a) x-z projection b) y-z projection and c) x-y projection. Both scales are in kiloparsecs.

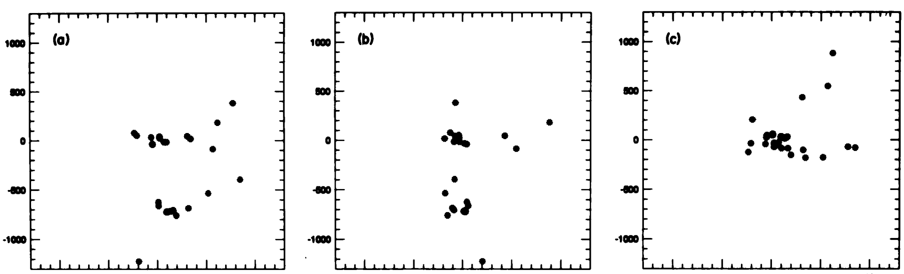

Figure 3. The local group galaxies in the same coordinates and projections as Fig. 2. Note the reduced scale.

distribution of objects around M31 is in fact similar to the Galaxy then there may be as yet undiscovered companion galaxies to M31 obscured by the Galactic plane.

3. Halo Field Star Surveys at $R_g > 25$ kpc

It seems unlikely that there are significant numbers of satellite galaxies left to be discovered around our Galaxy. Therefore, in order to make further progress in delineating the outer halo, we can look at the distribution of distant field stars. Table 1 summarizes some recent stellar surveys which extend beyond 25 kpc. The second column of the table indicates the kind of star used in the survey including RR Lyrae (RR) stars, blue-horizontal-branch (BHB) stars, carbon (C) stars and main sequence (m.s.) stars. The third and fourth columns of Table 1 give the Galactic latitude (b) and the latitude in the 'halo' coordinate system of Fig. 1 (b_h). It is not surprising

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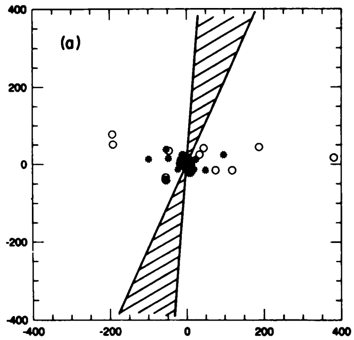

Figure 4. Same as Figs. 2 & 3 but with x-y coordinates rotated to project distributions in a plane perpendicular to the line of nodes to show the Galactic zone of avoidance (hatched area).

that most surveys have been done at relatively high Galactic latitude so that the leverage is poor for the detection of the flattening exhibited by the outlying systems. An exception is the Saha (1984) field with $b_h = -69°$. It is interesting to note that the faintest variable detected is 0.6 mag brighter than those in Saha's lower 'halo' latitude fields. The work by Bahcall *et al.* (1994) appears to be a promising way to probe the stellar halo to large distances (*e.g.* at $I = 25.3$, assuming $M_{V,TO} = 4$ and $(V - I)_{TO} = 0.6$ the limiting distance would be > 200 kpc). This assumes that the statistics are improved by looking at substantially larger areas and that unambiguous separation of faint main sequence stars from *stellar-like* extragalactic contaminants can be made.

4. The Density Profiles of the Three Luminous Components

Cursory examination of the radial extent of each of the distant components (stars, clusters and galaxies) suggests the existence of a nesting hierarchy in order of increasing spatial extension. In order to quantify this apparent tendency we have used the V/V_{max} statistic to determine the power γ in the following assumed density law:

$$\rho \propto s^{-\gamma} \tag{3}$$

where s is the distance measured along the minor axis of Fig. 1. The results are shown in Table 2 where the RR Lyrae star data is that of Saha (1984) and n is the number of objects in each solution for the indicated observed range in both R_g and s.

Clearly the results for the stellar component can and should be improved in the future. Confirmation of a nesting hierarchy could have important implications for the early evolution of the Galaxy.

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TABLE 1. Field Star Surveys ($R_g > 25$ kpc)

Survey	Objects	b	b_h	Area (sq.deg)	B_{lim}	B_{faint}	R_{gfaint} (kpc)
Saha 1984	RR	24°	-25°	44	19.5	18.7	40
		30	-22	44	19.5	18.9	43
		-29	-69	44	19.5	18.1	28
Hawkins 1984	RR	-47	14	16	21.0	20.0	59
Ciardullo *et al.* 1989	RR	70	33	–	—	V=19.2	52
Sommer-Larsen& Christensen 1986	BHB	-90	-14	18	V=18.7	V=18.6	38
		-51	-12	17	V=19	V=18.4	26
Sommer-Larsen *et al.* 1989	BHB	-51	-12	17	V=19	V=18.6	31
		-45	22	29	V=19	V=18.4	34
Norris & Hawkins 1991	BHB	-47	14	18	20.0	20.0	70
Arnold & Gilmore 1992	BHB	-62	-43	33	19.5	18.5	38
		44	29	33	19.5	18.8	40
Bothun *et al.* 1991	C	±90	±20	1400	V=16	V=16	50*
Richer & Fahlman 1992	m.s.	73	-2	0.012	I=24.5	—	65
Richstone *et al.* 1992	m.s.	-89	-14	0.002	25.0	24.8	?
Bahcall *et al.* 1994	m.s.	-51	4	0.001	I=25.3	—	?

* after elimination of dwarf carbon stars (Green *et al.* 1994)

TABLE 2. Density Law Exponent

Objects	n	γ	$R_g(kpc)$	$s(kpc)$
Galaxies	10	$2.8^{+0.3}_{-0.4}$	$25-400$	$24-101$
Clusters	13	$3.3^{+0.9}_{-0.9}$	$25-120$	$12-49$
RR Lyrae	10	$7.3^{+2.7}_{-2.4}$	$25-45$	$11-26$

5. The Outer Halo and the HI Warp

A common feature of many spiral galaxies is the existence of a warp in the outer parts of the disk. Our Galaxy is no exception, and a particularly good

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illustration of the warp of the Galactic HI is shown in Fig. 1 of Freudenreich *et al.* (1994) based on the data of Burton (1992). The most naive theory for producing warps has as its starting point a misalignment between the inner disk and an axisymmetric flattened outer halo. However, this naive theory has its problems which among other possibilities could be related to the existence of a triaxial outer halo (*c.f.* Binney 1992). As can be seen in Fig. 1 of Freudenreich *et al.*, the line of nodes of the Galactic warp is within $\sim 10°$ of the sun-centre line. The line of nodes determined from the distribution of outer satellites (defined by the intersection of the plane perpendicular to the minor axis of Fig. 1 and the Galactic plane) is 216°. This difference, $\sim 36°$, is probably not significant given the uncertainties in the model. Finally, we note that at least the sign of the warp is in agreement with intuitive expectation (*i.e.* above the plane in the first two quadrants and below in the last two). In summary, our understanding of the cause of warps is incomplete at present but it seems likely that there will be a close connection between the structure of the outer halo and the Galactic warp.

6. Summary and Discussion

The main results of this work can be summarized as follows. By fitting a three dimensional surface to Galaxy satellites beyond 25 kpc it is found that both the globular clusters and satellite galaxies show highly flattened spatial distributions whose minor axes are aligned to within $\sim 5°$. Such a situation which implies a close connection between the two groups of objects is extremely unlikely to have arisen by chance on the assumption that objects in both groups were drawn from an isotropic angular position distribution. The surface determined from the combined sample of 23 objects is a triaxial ellipsoid whose semimajor axis is ~ 400 kpc in extent. The orientation of the principal axes are shown in Fig. 1. The minor axis of the ellipsoid is inclined at 75.5° to the direction of the Galactic pole. When all of the local group galaxies are plotted in the new coordinate system (Fig. 3) one finds that the minor axis of the Galactic system points approximately in the direction of M31 and, in addition, the suggestion that the distribution of M31 satellites may be mimicking that of the Galaxy. A summary of recent stellar surveys to distances > 25 kpc is given. The available data are not inconsistent with the distribution found for the outer satellites but deeper surveys, especially at low Galactic latitudes, are still required. Finally, from the density profiles there is marginal evidence that the various components (*i.e.* stars, clusters, and satellite galaxies) are nested in order of increasing spatial extent. Figure 5 is a sketch along the major axis of the Galaxy and attempts to illustrate what has been found above.

Recent N-body calculations of dissipationless collapse (*e.g.* Frenk *et al.*

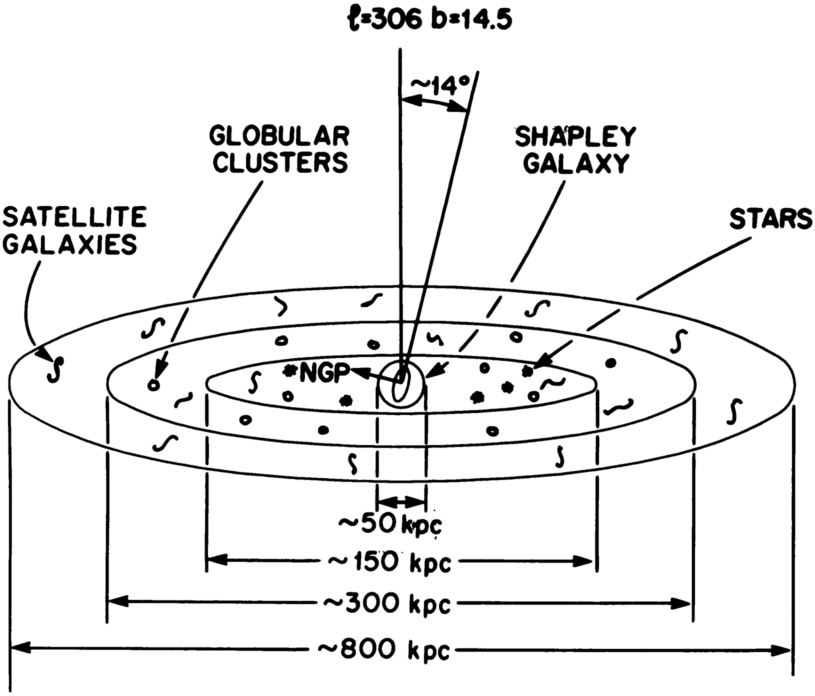

Figure 5. Summary sketch showing rough major axis dimensions of the stellar, globular cluster and satellite galaxy components. Note the orientation of the north Galactic pole (NGP).

1988; Dubinski & Carlberg 1991; Warren *et al.* 1992) show that the dark halos are triaxial with c/a$\sim$ 0.5 and b/a$\sim$ 0.7. The halos should become more oblate if a small dissipative component is included (Katz & Gunn 1991; Dubinski 1994). The fact that the ellipsoid found here has much more extreme flattening may be a reflection of the fact that *dissipational* tracers are being used to determine the shape. On the other hand, the misalignment between the Galactic disk and the minor axis, as well as the formation of a warp, seems not at all unusual in the hierarchal merging picture (*c.f.* Katz & Gunn 1991).

The outer satellites which we associate with the Galaxy extend as far away as 390 kpc. In a recent study involving the correlation in redshift of galaxies and QSO absorption line systems Lanzetta *et al.* (1994) have found in one case a Lyman α system with impact parameter 347 h^{-1} kpc. Clearly, an extended galaxy provides a rationalization for such a result. Furthermore, as the Katz & Gunn models evolve, gas collects in the cores of dark matter clumps. These structures resemble (for a time) the minihalos of Rees (1986) which have proved so successful in explaining the high redshift Lyman α absorbers. Because of limited resolution, the fate of these minihalo-like structures in the outermost parts of the Katz & Gunn models (where collisions are rare) is not clear. However, one can imagine at least three endpoints: a) the gas cools and condenses into stars and forms what may eventually resemble a dwarf spheroidal galaxy, b) the gas is not able to condense and remains a candidate for a Lyman α absorption line observation, and c) two minihalos may occasionally collide possibly forming a globular cluster in the process. When combined with the inner stellar spheroid which *is* seen in the models (Katz 1992), one could have a natural explanation for the observed nesting hierarchy.

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DISCUSSION

J. Binney: Cen A is certainly a system in which gas on a small scale is rotating about an axis that is the long axis of the large-scale stellar distribution. Such systems seem to form often enough in the chaotic conditions of N-body models since gas and collisionless particles are subject to very different pressure. If this sort of thing is known to happen on a small scale, there seems every reason to expect its occurrence on larger scales, which have had less time to settle to an ordered state. (no reply necessary)

B. Burke: The c-axis of the "Shaply Galaxy" is nearly at right angles to the larger system that you derive. It contains most of the mass, and is triaxial, but predominantly oblate. This would dominate the potential, so the orthogonality might seem surprising (although we know of such systems). Any comment on this?

Hartwick: (*followed by Hartmann, referring to Binney's result*) So the orientation is an accident.

K. Freeman: Can you say anything about the kinematics of this outer triaxial halo system? It would be interesting to look for systematic motions in a system that is so elongated.

Hartwick: I have not yet looked at the kinematics in detail.

U. Haud: The fact that the companions of giant galaxies are preferentially concentrated to the plane, nearly perpendicular to the plane of main galaxy was first mentioned by Holmberg (1969). We have made corresponding analysis using the data on several tens of nearby groups of galaxies and confirmed such preferred concentration using both, the data on spatial distribution of companions and on their kinematics. Our results are published in A & A vol. 229, p. 47 (1990).

L. Ozernoy: You have illustrated convincingly how the size of the Milky Way Galaxy had grown in accordance with the operational definition of the Galaxy, from 2kpc to 800kpc. Bearing in mind the dark halos of the galaxies it seems possible that the dimensions of M31 and our galaxy's halos are overlapping. If the dark matter of these both galaxies is, in a sense, a common substance could we still consider the galaxies as being isolated?

Hartwick: That is possible since even the most extended light tracer may be biased i.e. may not be tracing the mass distribution.

J. Sellwood: There is a suggestion from the work of Quinn & Goodman that satellite galaxies with orbits lying close to the plane of a disc galaxy suffer more rapid dynamical friction than those which orbit over the pole. Wouldn't such an effect bias your estimate of the halo shape?

Hartwick: As I understand it, there may not be enough time for the Quinn-Goodman process to operate on the most distant objects but the question should be investigated in more detail.