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## The Milky Way as a Key to Structural Evolution in Galaxies

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**Abstract.** Much of our effort in understanding the long-term evolution and morphology of the Milky Way and other galaxies has focused on the equilibrium of its luminous disk. However, the interplay between all components, seen and unseen, is a major cause of observed features and drives evolution. I will review the key underlying dynamics, and in a number of examples, show how this leads to lopsidedness and offset nuclei, may trigger bars and cause warps. Indeed, the Milky Way like most spiral galaxies show exhibit many of these features. In addition, the mechanisms suggest that observed morphology depends on the properties of the galaxy and only weakly on any particular disturbance. Because of this convergence, understanding a galaxy's history will be subtle and require the level of detail that study of the Milky Way can provide.

### 1. Introduction

In introductory and graduate astronomy textbooks alike, the Milky Way is used as an introduction to galaxies in general; clearly Galactic astronomy and the astronomy of galaxies has evolved together. Most recently, the study of evolution and morphology at high redshift, e.g. motivated by studies of the Hubble Deep Field and the Medium Deep Survey are leading to revisions of the standard paradigms for galaxy morphology and evolution. Ironically, it appears that one legacy of the HST may be abandonment (at least in part) of the Hubble galaxy classifications (e.g. Conselice et al. 2000).

At the same time, computational technology is nearly keeping up with observational technology. Computation allows complex non-linear prediction through simulations and statistical inference on large data sets. The scientific questions remain familiar:

- Where does structure in galaxies come from?
- What excites star formation?
- Where is the mass in a galaxy?
- What is its role in causing the observed structure?

What is increasingly clear is that any individual galaxy is morphologically variable. For example, lopsided ( $m = 1$ ) asymmetries are transient (with gigayear timescales), bars may grow slowly or suddenly and, under some circumstances may decay as well. Recent work shows that stellar populations, star formation rates and color depend on asymmetry (e.g. Rudnick, Rix & Kennicutt 2000). Because the properties of a galaxy

depend on its history, an understanding of galaxy evolution requires that we explore the possible scenarios and underlying mechanisms. This same goal motivated the dynamicists of the past several decades and led to our current understanding of density waves, instability and stability criteria. Unfortunately, gravitational dynamics is also conspiring against our investigation of long-term evolution as I will describe. In short, a galaxy responds to a wide variety of stimuli and over many gigayears the historical record of specific events fades away. Because state-of-the-art and planned surveys will allow us to study the global structure Milky Way in detail, our Galaxy will be key to this understanding.

The overall plan of this talk is as follows. I will begin with a cartoon review of galaxy dynamics, emphasizing asymmetries, since it is through asymmetries that a galaxy evolves. I will illustrate this with a review of asymmetries in the Milky Way. We will see that the role of satellites and dwarfs may be significant. Finally, I will briefly list the role of upcoming missions and surveys.

## 2. A cartoon review of galactic dynamics

Fundamentally, all asymmetric structure in stellar systems is transient. Although early work in galactic structure emphasized modes, this same work showed that these modes were different than the familiar discrete modes of plucked strings and drumheads. Systems with very large numbers of degrees of freedom have continuum modes, in addition to the more familiar discrete modes, which allow for both global redistribution and dissipation. A physicist might say: “Spiral arms and bars are a galaxy’s way of attempting to reach its minimum energy state.” The dynamicist might say: “Any feature with non-zero pattern speed must damp through resonance with the stellar orbits.” Either way, the end result is transient features which change the morphology of a galaxy. Let me give you three familiar examples and one similar but less familiar case.

### 2.1. Swing amplification

Swing amplification, a widely used dynamical model for understanding the structure and ubiquity of arms, contains all of these elements. The following cartoon (based on Toomre 1980 and Binney & Tremaine 1987) of this mechanism first described by Goldreich & Lynden-Bell (1965) illustrates the basic mechanisms.

If one takes a small patch out of a galactic disk, it will look like the situation in the first frame in Figure 1. The LSRs of orbits appear to lead (trail) as one looks inward (outward) from the center of the galaxy. The epicyclic motion about the LSR of an individual orbit is shown. Now assume that a leading material arm appears (2nd frame). We follow an individual star (filled dot) as this distribution evolves. The material arm shears out (successive frames) but the star feels the excess gravitational attraction of the arm as it shears, amplifying the arm.

A nice simulation of this has recently been reported by (Demleitner 1998) for both stars and gas together. The imposed leading distortion “swings” quickly and amplitude of the trailing arm increases and then damps away.

Swing amplification is a simple example of transient behavior induced by a gravitational perturbation. In the end, a quiet isolated galaxy may attain a new local axisymmetric state but with a slightly different equilibrium state since the arm has transferred angular momentum from some stars to others. The shape of the resulting arm depends

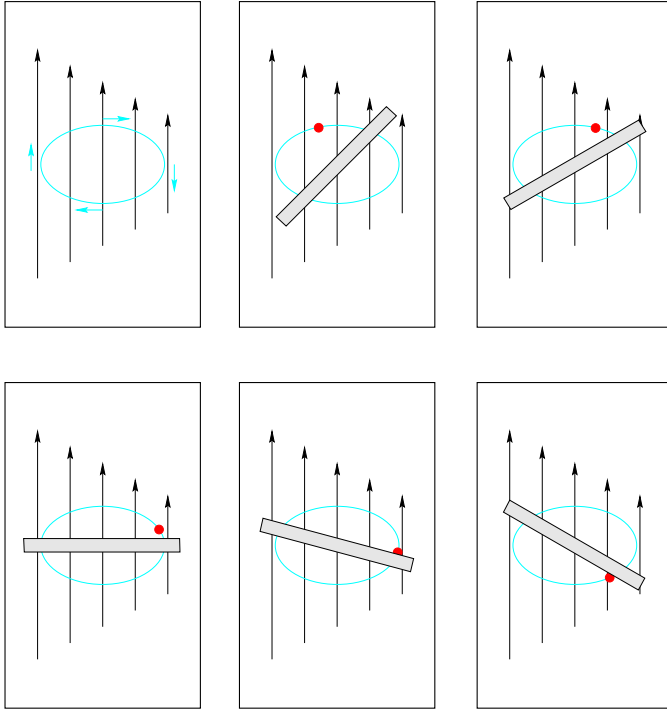


Figure 1. Cartoon illustrating swing amplification in a shearing sheet (following Binney & Tremaine 1987). The vertical arrows indicate the relative velocity of the local LSR. The epicyclic orbit in the LSR of the central trajectory is an ellipse and the position of the star is the filled dot (first panel). Successive panels show the time evolution of a leading spiral perturbation. The trajectory of the star tracks and reinforces the perturbation.

more on the underlying dynamics of the disk (e.g. Oort constants) than the details of the triggering distortion.

## 2.2. Bar formation

Dynamicists argue whether bars form suddenly, as in the sort of instability that led Ostriker & Peebles (1972) to advocate a dark halo, or slowly over many rotation times (Pasha & Polyachenko 1993). Either way, the mechanism has a similar explanation.

A general orbit in an axisymmetric disk is a rosette. However, by accelerating an observer around the disk at a particular angular velocity, the orbit can be made to nearly close (Fig. 2). Averaged over time, the orbit appears to hang out at its outer turning points. You might imagine, therefore, replacing the orbit's average mass density by a dumbbell (final panel).

Now imagine two such orbits. If this was a Cavendish experiment, the ends of the dumbbells would attract. However, recall that these are *real* orbits and we are observing them in a rotating frame. Depending on the background potential, the material torque can cause the two orbits to precess toward either each other or away from each other. Lynden-Bell & Kalnajs (1972) give a precise criteria for this but the general rule is that orbits precess toward (away from) each if the rotation curve is rising (flat).

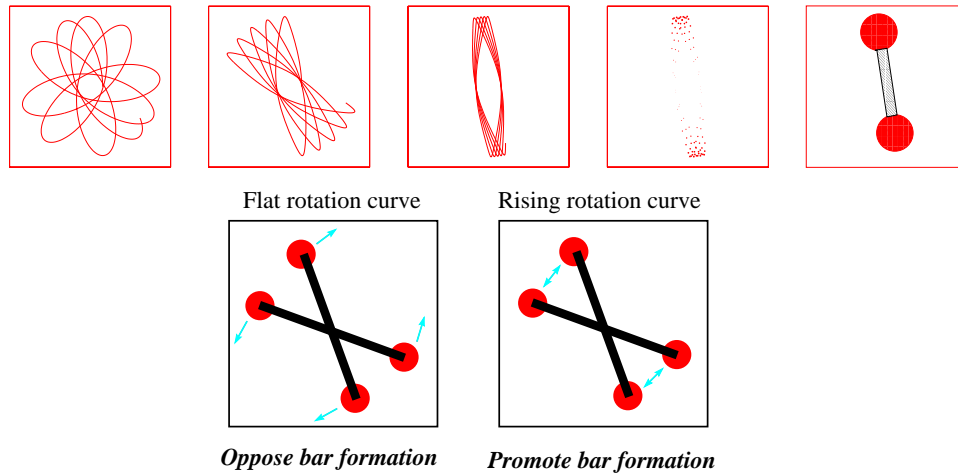


Figure 2. Cartoon illustrating bar instability and growth. Top row: orbit approaching resonance in first three panels; fourth panel shows the location of a star at fixed time intervals showing that the orbit has higher time-averaged space density at apocenter and can be represented by a dumbbell (fifth panel). Bottom row: excess density repels apocenters for a flat rotation curve but attracts for rising rotation curve, causing bar to grow.

As the process continues, the gravitational potential from the pile of apoapses increases the influence or *reach* of the torque and more orbits can be influenced to join the crowd. This is clearly the description of an instability and it leads to the formation of an  $m = 2$  bar. Thinking like a physicist again, it is favorable for the bar to exist because the particles that take part lower the energy of their configuration. In this way, bar formation may be understood by analogy with self-gravitating fluid bodies (e.g. Chandrasekhar 1969). In the presence of a bit of dissipation, a rapidly rotating spheroid will adopt a prolate shape because it can do so by lowering its energy. Similarly, energy (and angular momentum) is redistributed by the formation of a bar. Again, the location and structure of the bar has more to do with the galactic potential and disk distribution than the perturbation which started off the instability. Once the bar has formed, it may continue to influence the evolution of a galaxy; the existence of a strong non-axisymmetric structure can continue advect angular momentum both to the disk and halo, acting as an angular momentum antenna (see Debattista & Sellwood 1998 for a recent discussion). In summary, the existence of a bar implies a process of continuing evolution.

### 2.3. Halo modes and noise

Now, a gravitational halo itself can sustain modes, and not unlike those of a disk, these modes damp. These are less well-known because they are not practical to observe (however, see the end of this talk) but can be worked out and detected in n-body simulations. A halo dominates the outer galaxy and is significant in the inner galaxy and therefore persistent halo distortions can be quite important even though these can not be observed directly.

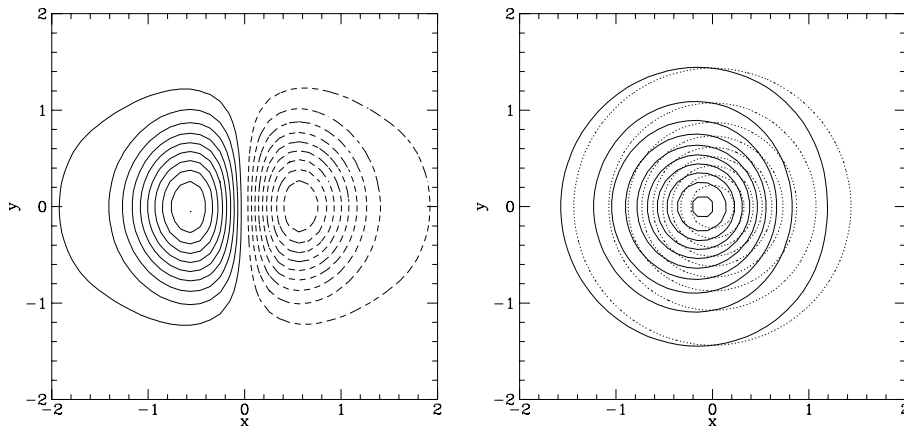


Figure 3. Weakly damped mode in  $W_0 = 5$  King model. Left: the density eigenfunction in the symmetry plane. Overdensity (underdensity) is indicated by the solid (dashed) contours. Right: density profile of the mode in the halo (solid line) compared with the profile without the mode (dotted curve).

The strongest of these halo modes is an  $m = 1$  or sloshing mode and damps surprisingly slowly. An example is shown in Figure 3 for a King model for clarity. These modes exist for all typical halo models (e.g. Hernquist models [Hernquist 1990], NFW profiles [Navarro, Frenk & White 1997]) and do not depend on the existence of a core. A qualitative explanation for the slowing damping is as follows. A coherent mode damps through resonances between its pattern speed,  $\Omega_p$  and the orbital frequencies,  $\Omega_r$  and  $\Omega_\phi$  of individual stars. At  $l = m = 1$  order, the damping is a resonance between these frequencies of the form:  $\Omega_p - l_\phi \Omega_\phi - l_r \Omega_r = 0$ , where  $l_\phi \in \{-1, 0, 1\}$  and  $l_r \in \{-\infty, \dots, \infty\}$ . For vanishingly small  $\Omega_p$ , the only orbits near resonance are Keplerian and therefore at outer edge of the galaxy. If the system can have a discrete  $l = m = 1$  mode at small pattern speed, the resonant orbits that can cause damping will be at large radii and the damping will be small. This is exactly what happens.

In the inner galaxy, many studies suggest or assume that the disk dominates the gravitational potential. Perhaps this reduces or eliminates the  $m = 1$  halo mode? Not so! The disk and halo can have a mutual weakly damped  $m = 1$  mode. The quadrupole mode is weakly amplified by self-gravity but most others appear to damp quickly. The  $m = 1$  mode is very easy to excite. Because the halo may contain most of the mass of the entire galaxy, a relatively small halo disturbance can result in a large perturbation of the disk. For example, the Poisson noise from a halo of  $10^6 M_\odot$  black holes can produce a mode with potentially observable consequences. An orbiting satellite or shot noise caused by accreting massive HVCs and dwarfs can all potentially excite the  $m = 1$  mode. Finally, we tend to think of a galaxy as in equilibrium, however the orbits in the outer halo have very long periods (several Gyr); therefore phase mixing is another source of noise (Tremaine 1993).

Although I have emphasized the  $l = m = 1$  sloshing modes, there are also  $l = m = 2$  bar-like modes. These quadrupole responses have a shorter damping time than the sloshing mode and this can be understood by the same sort of argument: for a non-zero

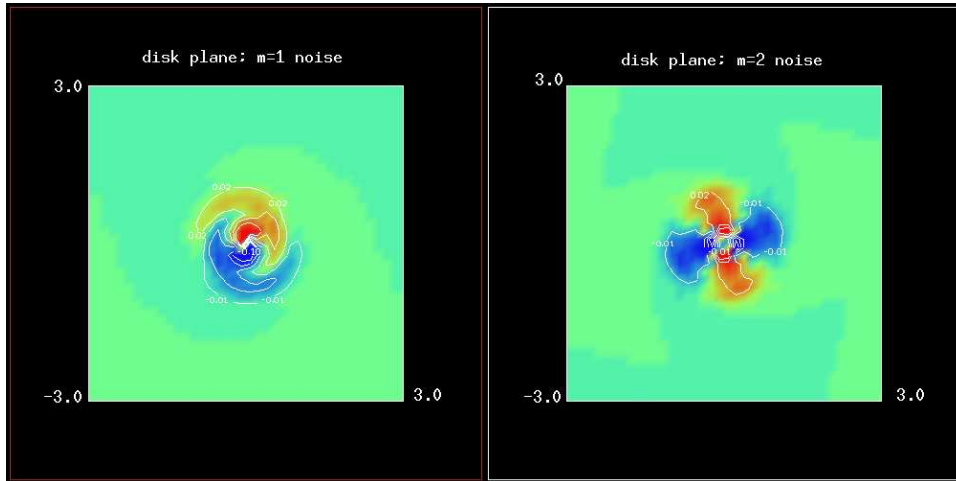


Figure 4. Density fluctuations due to halo particle noise ( $N = 10^6$ ). Amplitude of the  $m = 1$  response (left) is roughly ten times the amplitude of  $m = 2$  response (right).

$\Omega_p$  there are more and closer stellar orbits with resonances of the form  $2\Omega_p - 2\Omega_\phi - l_r\Omega_r = 0$ . Higher order halo modes damp more quickly.

Why haven't these modes been seen in n-body simulations? There are two answers to this question. First, they have been or at least their effects have been. Weakly damped modes will be excited by Poisson fluctuations and provide excess power at their natural scales. Analyses of n-body simulations show that this excess power is there exactly at the location and amplitude predicted by the dynamical theory. Secondly, detecting the pattern itself is much harder because the pattern speed is slow and the noise in most n-body simulations is sufficient to wipe out the mode in a few crossing times. This is too short a time for the mode to set itself. A sufficiently quiet simulation requires many millions of particles.

As an example of the excess power, Figure 4 shows the effect of the modes on the response to particle (Poisson) noise. The left-hand (right-hand) panel shows the overdensity for  $l = m = 1$  ( $l = m = 2$ ). The overdensity pattern is dominated by the mode. The  $l = m = 2$  profile is an order of magnitude smaller than  $l = m = 1$ , and both exceed that expected by Poisson fluctuations alone. Higher order harmonics are consistent with the expected Poisson amplitudes (see Weinberg 1998a for additional details). This illustrates a general feature of halo dynamics: the response to a transient disturbance will be dominated by the weakly damped modes, independent of the details of the disturbance.

## 2.4. Bending and warps

Warps in the outer galaxy reveal some combination of the halo and disk properties, the galactic environment and history. This promise of disk warping as a probe of the gravitational potential has led to numerous theoretical and observation campaigns (see Binney 1992 for a review). Whether forced by an external perturbation such as a dwarf galaxy, accreted material or a rotating triaxial halo, warping and bending of the disk may be considered as a response. Just as in the case of the halo, these features will

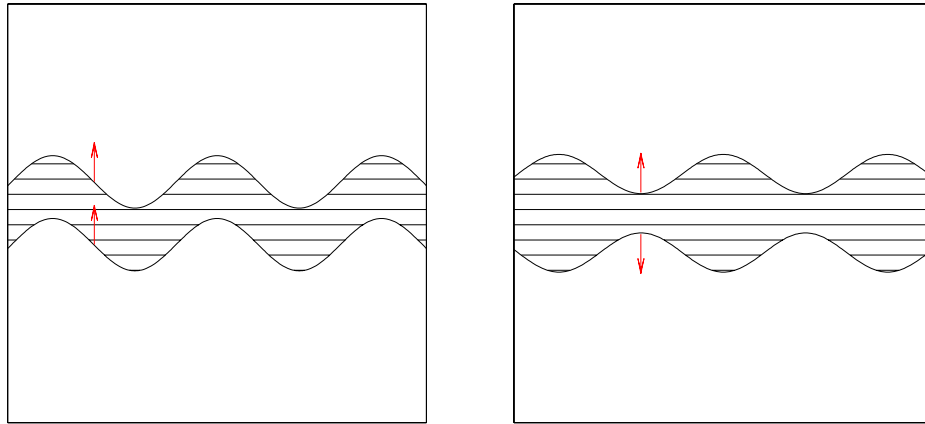


Figure 5. Bending modes in a stellar slab. Careful solution shows that there are two sorts of modes, an odd or *bending* mode (left) and an even or *breathing* mode. The bending mode is purely oscillatory in the limit that the vertical velocity dispersion vanishes relative to the in-plane velocity dispersion. The breathing mode is the damped analog to the Jeans' instability and approaches the unstable Jeans' mode as the velocity dispersion decreases. The arrows indicate the instantaneous direction of the slab for each type of mode.

be generic. A good toy model is a slab of stars of infinite horizontal extent but finite vertical extent. The limiting case, an infinitesimally thin stellar slab can sustain bending modes. In general, both bending and breathing modes exist (see cartoon in Fig. 5). As one thickens the slab, these bending modes begin to damp (Weinberg 1994). The damping results from a coupling between the bending and the vertical degrees of freedom in orbits making up the disk. If you perturb an slab with projectile, it will begin bend. However, the thicker the slab (ratio of vertical to in-plane velocity dispersion), the faster the damping.

The generalization of this simple slab to an thin axisymmetric disk is due to Hunter & Toomre (1969) and since has been invoked to explain disk warps (e.g Sparke & Casertano 1988, Hofner & Sparke 1994). More generally, a warp may be a player in a much larger nested set of distortions. For example, Weinberg (1998b) suggests the possibility of a warp created by a distortion from the orbiting LMC. The LMC first excites a wake in the halo. The halo distortion will be similar in shape to those depicted in Figures 3 and 4. But because the LMC orbital plane is highly inclined this wake can differentially distort the disk plane and the disk response is a warp (more on this in §4.1.). This final topic points out that all of these distortions may be simultaneous and connected, and at the very least, a disturbance in the halo or disk should not be considered independently.

### 3. Milky Way asymmetries

Threaded through the dynamical overview is the importance of the underlying galactic structure in forming a response, independent of the excitation. Before we put the whole picture together, let us take stock of the Milky Way asymmetries. The Milky Way shows evidence for every type of asymmetry described above:

1. The Milky Way has a bar. This has been demonstrated in many tracers: surface brightness (COBE), star counts, gas and stellar kinematics and, as originally postulated by de Vaucouleurs, based on morphology (de Vaucouleurs & Pence 1978). Recent work by Englmaier, Gerhard and collaborators shows this quite convincingly (e.g. Englmaier & Gerhard 1999).
2. The Milky Way is lopsided. In fact, it is lopsided both in the inner kpc and the outer 30 kpc! The former asymmetry is clearly seen in the molecular gas (e.g. Blitz et al. 1993) and the latter is evident in the HI analysis presented by Henderson et al. 1984.
3. The Milky Way is most certainly warped. This is also clearly seen in the HI layer (Henderson et al. 1984). The line of nodes is roughly  $l = 0^\circ$ . The HI layer reaches nearly 3 kpc above the plane at edge of the stellar disk ( $R \approx 16$  kpc) and this is echoed in the molecular gas layer (Heyer et al. 1998). There is evidence for a stellar warp as well (Djorgovsky & Sosin 1989, Carney & Seitzer 1993) but recent analysis based on Hipparcos data (Smart et al. 1998, Drimmel et al. 1999) show that some mysteries remain.
4. The shape of the halo is less certain. Recent results claim both flattened and round. Two arguments for a flattened halo have been recently presented by Olling & Merrifield 2000. The first is based on the Milky Way rotation curve and the local stellar kinematics. The second assumes that the HI is in hydrostatic equilibrium and uses the magnitude of gas-layer flare to estimate the vertical force and therefore the halo shape. Both methods yield a ratio the short to long axis of  $q \approx 0.8$ . A recent preprint by Ibata et al. 2000 argue that  $q \approx 1.0$  based on the nearly great-circle appearance of carbon stars attributed to the Sgr A dwarf debris trail. Any significant deviation from spherical would cause the stream to precess and produce smearing which is not seen.

Is this amount of asymmetries unusual? Or is it the case that no galaxy is normal when you look closely? First, anecdotally or based on counting morphological types in the RC3, a significant fraction (roughly 40%) of galaxies are barred! This turns out to be a stronger result in near-infrared; Eskridge et al. (2000) show that 72% of spirals are barred (strongly or weakly). This is expected theoretically as the discussion in §2.2. illustrates. The trapped orbits that make up bars must be dynamically old and therefore relatively red compared to colors of populations with recent star formation. Second, all galaxies have dwarf companions that may trigger asymmetries. In an ambitious project designed to measure the mass of dark halos, Zaritsky and collaborators observed dwarfs around isolated field galaxies. Their census shows that the average number of companions of the LMC sort are 1.4 (Zaritsky et al. 1997). The LMC luminosity is a “one sigma” on the bright side of the mode. Similarly there are both closer and more distant dwarfs. In short, we can expect most spirals to have a nearby dwarf companion. Third,

Table 1. Is the Milky Way typical?

All galaxies	Milky Way
72% barred (weak and strong in H-band)	Barred (SAB), 4-arm spiral
1.4 major satellites/spiral galaxy	Magellanic Clouds, +
~ 50% warped	Warped
~ 5% optical, ~ 50% HI lop-sided	Lopsided center, outer HI
Nearly all galaxies have halos (inferred)	10:1

References:

Eskridge et al. 2000 (bar fraction  $t$ -independent)

Zaritsky et al. 1997

Reshetnikov &amp; Combes 1998

Rudnick, Rix, Kennicutt 2000

what about warps? Statistics on warps are more difficult to obtain but roughly half of spirals have outer warps (Binney 1992, Burton 1998) with later types predominating (Bosma 1991). Anecdotally, people who look hard at morphology claim that all spiral galaxies are warped. Fourth, more than half of spirals appear to be lopsided in HI (Swaters et al. 1999) and 20% of all disk galaxies (Rudnick & Rix 1998) and a recent paper by Rudnick, Rix & Kennicutt (2000) estimate that 5% are lopsided in the optical.

Table 1 shows summarizes these facts. In short, all galaxies seem to show very similar sorts of asymmetries. Because the halo dominates the mass of a galaxy we expect that any non-axisymmetric structure in a halo will be manifest in the lower-mass luminous component. The strongest easy-to-excite feature, the  $m = 1$  mode, can cause both lopsidedness and warps as I am about to describe.

## 4. Satellites and dwarfs

### 4.1. The LMC

Hunter & Toomre (1969) explored the possibility of the LMC being the source of the Galactic warp and found that a direct tidal perturbation only resulted in a warp with an amplitude of 50 pc! Of course, this predated the dark matter paradigm and the halo was not included. A major part of the same wake that causes LMC to decay by dynamical friction is the dipole and quadrupole distortions, amplified by the self-gravitating mode discussed earlier<sup>1</sup>. Because the LMC is on a polar orbit the response is not in the disk plane and the wake will exert a differential vertical force on the disk. In particular, the quadrupole distortion can cause an integral-sign shaped warp (see cartoon in Fig. 6 for an explanation). The dominant effect of the dipole will be a center of mass shift. The warp is strongest if the pattern speed of the warp is close to the pattern speed of the halo wake. It turns out that the LMC is nearly in an ideal position for this to happen. In addition, the dipole part ( $m = 1$ ) causes a significant in-plane asymmetry in the outer part of the halo quite similar to the Henderson et al. (1984) figure discussed earlier.

<sup>1</sup>In fact, one can show rigorously that the response of the halo, the wake, attracts the satellite that excited it with exactly the force predicted by dynamical friction theory which then causes the satellite orbit to decay.

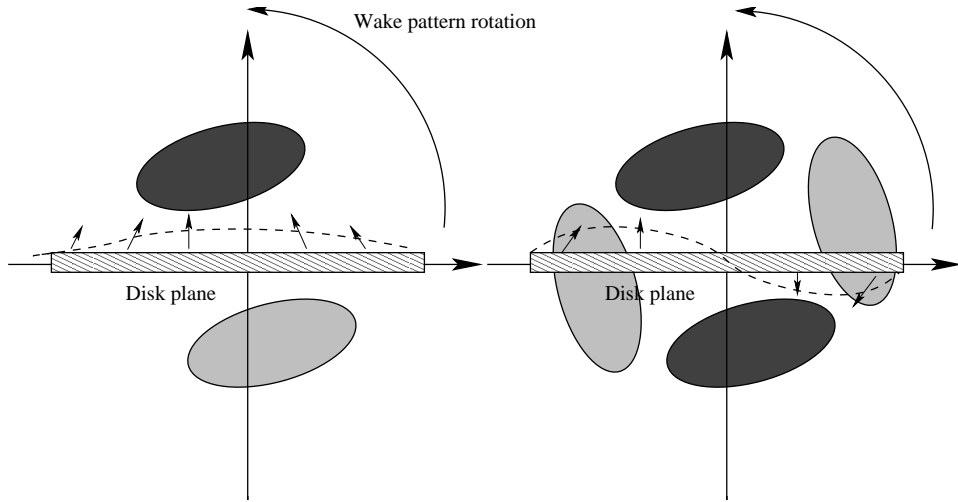


Figure 6. Sketch showing the differential force on a disk from a dipole wake (left) and quadrupole (wake) right. The dark and light grey ovals indicate overdensity and underdensity, respectively. In the dipole ( $l = m = 1$ ) case, the force is one sided, giving rise to a dish-shaped distortion. In the quadrupole ( $l = m = 2$ ) case, the force is bisymmetric giving rise to an integral-sign shaped distortion. The dashed lines indicate the expected shape of the warp in each case.

Some recent work (Garcia-Ruiz, Kuijken & Dubinski 2000) has suggested that the LMC can not be the source of warp because the response will be in phase with the satellite. A detailed study of the response reveals that the mean position angle of the outer wake is roughly aligned but, the inner wake trails considerably (greater than  $45^\circ$  at various points in the orbit). Physically, this phase lag must occur in order for there to be any dynamical friction; it is the attraction by the wake that causes the drag. The halo wake is not just an added enhancement to the satellite torque but dominates the direct satellite perturbation by nearly an order of magnitude inside of half the LMC orbital radius. This inner wake is dominated by a higher-order resonances (the 2:1 resonance is often strong). It is likely that the parent orbits for such a resonance could exchange stability and appear aligned rather than perpendicular. To summarize, the amplitude and morphology of the wake will depend on details galactic potential and the satellite orbit, but conversely is not strongly constrained by orbital positional angle. Although a strong warp requires a nearby resonance, this obtains for a broad range of conditions.

Scalo (1987) argued the possibility that the Milky Way and the LMC have time-synchronous bursts and this is consistent with the chromospheric age work by Barry (1988). Although it is easy for the LMC to be strongly affected by the tidal field of the Milky Way (Weinberg 2000), it is more difficult for the LMC to affect the Milky Way. This is only a suggestion, but note that resonant excitation of the halo modes is a plausible mechanism.

Just as interesting is the effect of the Milky Way on the local group dwarfs. After working hard to understand the LMC-induced Galactic structure, I have recently been impressed with the damage that may be done to a dwarf by the Milky Way. Dwarfs within roughly 100 kpc are likely to be tidally limited. By definition, the gravitational

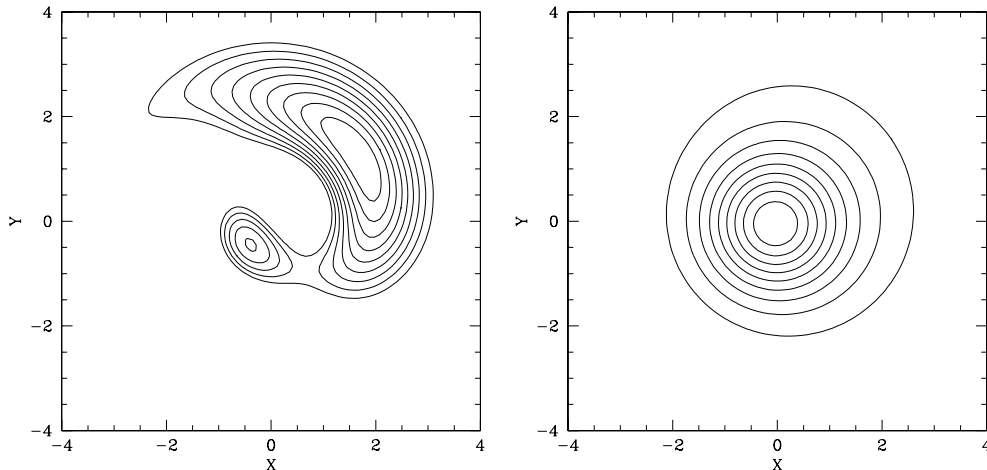


Figure 7. Left: shape of  $m = 1$  in-plane distortion for a  $2 \times 10^{10} M_{\odot}$  LMC mass. Right: the isodensity profiles for this distortion. Note that the inner galaxy is shifted in the opposite sense as the outer galaxy, however, unless there is a way of inferring the unperturbed center, this would not be measurable.

force of the Milky Way on mass at the tidal radius is of the same order as the gravitational force exerted by the dwarf. At half the tidal radius, the tidal force is roughly an order of magnitude smaller but a 10% perturbation is still significant and leads to a number of interesting responses:

1. Disk heating: the dependent forcing as the dwarf moves on its orbit can heat the disk noticeably in several gigayears.
2. Precession: the disk plane is unlikely to be coplanar with the orbital plane, the resulting torque will cause the disk to precess. This leads to a complex interaction between the global torque, halo + disk back reaction and resonant heating.

This complex interaction should lead to disk warping and other differential distortions. This motivates an increasingly detailed study of the LMC-Milky Way interaction which may help us appreciate a suite of more general problems. For example, will this complex of dynamical mechanisms destroy a disk to make spheroidal? Will the heating exacerbate loss of equilibrium in the Galactic tidal field leading to stellar and gaseous streams? More quantitatively, can we predict the disruption rate?

#### 4.2. Dwarf fly-by events

Another way of getting the same sort of excitation, perhaps more important for group galaxies than the Milky Way, is a passing fly by. A perturber on a parabolic or hyperbolic trajectory can excite similar sorts of halo asymmetries and persist until long after the perturber's existence is unremarkable. Presumably, our Galaxy has suffered such events in the past but because the satellite excitation is closely related to the fly-by excitation, the study of one will provide insight into the other. The upper left and right panels of Figure 8 show the non-axisymmetric  $m = 1$  part of the disk and halo

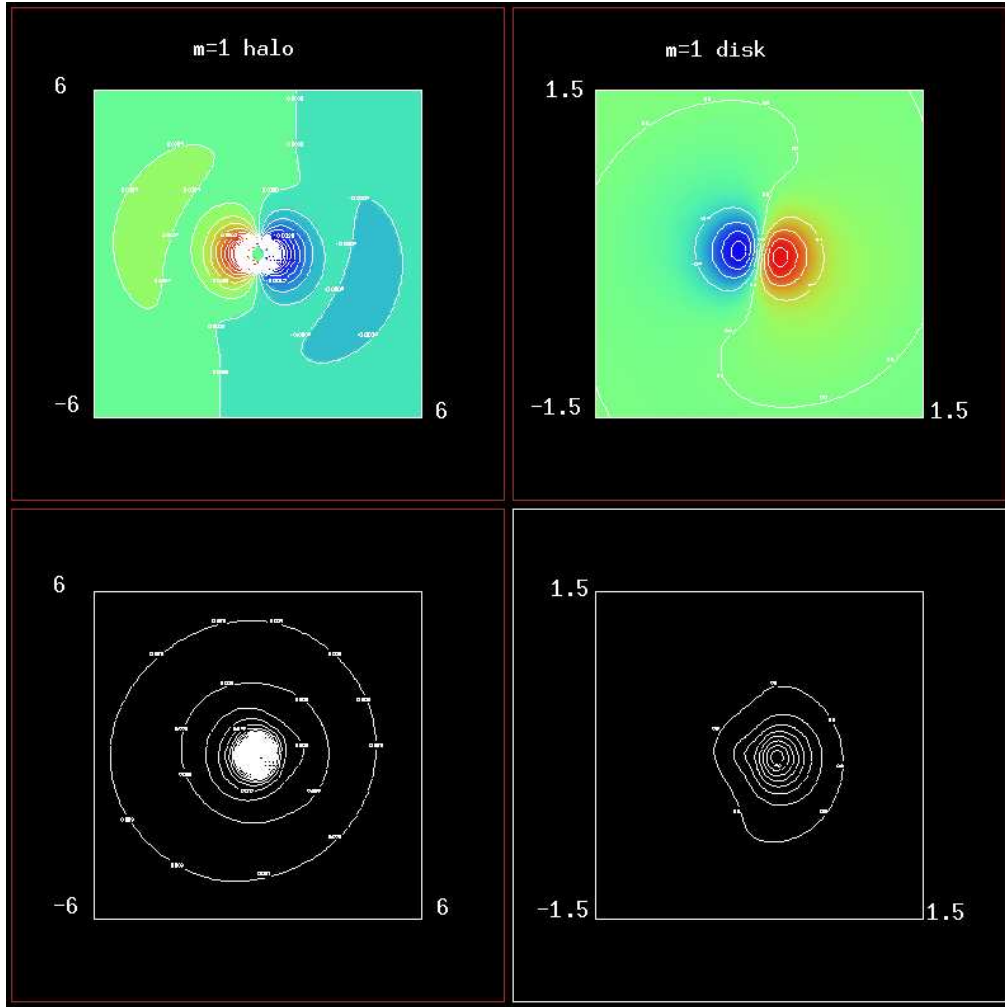


Figure 8.  $m = 1$  halo (upper left) and disk (upper right) response to a perturber flying by on the disk plane. Lower panels show the total halo (left) and disk (right) density on the  $x - y$  plane (from Vesperini & Weinberg 2000b). Notice that the disk and halo responses are anti-correlated.

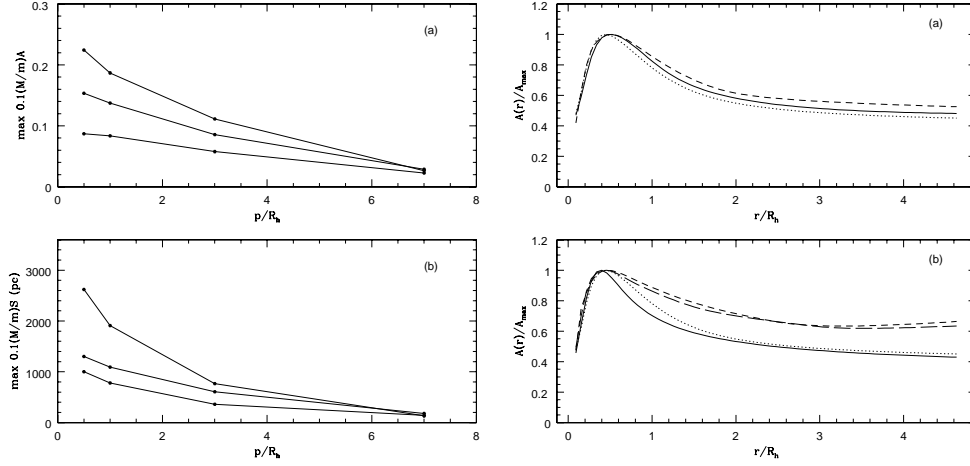


Figure 9. Top left: Variation of asymmetry parameter  $A$  with pericenter  $p/R_h$  for perturbers with 10% of the galactic halo mass (scaling shown). The three curves correspond (from the upper to the lower curve) to  $V = 200, 500, 1000$  km/s. Bottom left: Center-of-mass offset in parsecs for the same events. The three curves correspond (from the upper to the lower curve) to  $V = 200, 500, 1000$  km/s. Top right: Radial profile of  $A$  normalized to its maximum value for fly-bys with  $p/R_h = 1.0$  and  $V = 200$  km/s (solid line),  $V = 500$  km/s (dotted line),  $V = 1000$  km/s (dashed line); each curve corresponds to the radial profile of  $A$  when the total  $A$  is maximum. Bottom right: Same as top right but for fly-by with  $V = 500$  km/s and  $p/R_h = 0.5$  (solid line),  $p/R_h = 1.0$  (dotted line),  $p/R_h = 3.0$  (dashed line),  $p/R_h = 7.0$  (long dashed line).

perturbation from an n-body simulation (Vesperini & Weinberg 2000b). The perturber trajectory is on the  $x$ - $y$  plane with pericenter at 70 kpc and mass twice that of the LMC. The lower left and right panels of Figure 8 show the resulting halo and disk distortion. The distortion in the disk plane closely follows that in the halo. This example has a dramatic distortion but smaller effects would be easily detectable.

The n-body simulations agree in magnitude and morphology with the perturbation theory. The perturbation theory allows us to scale the encounter by velocity and impact parameter (or their ratio if the perturber is completely outside of the halo). From the analytic calculations, we can compute the standard asymmetry parameters (e.g. Abraham 1996a, Conselice et al. 2000) obtained by summing over the mean square difference of the galaxy and its  $180^\circ$  rotated image:

$$A = \frac{1}{2} \frac{\sum |I(x, y) - I_{rot}(x, y)|}{\sum I(x, y)}. \quad (1)$$

The results are shown in Figure 9 (upper left) which shows the maximum value of  $A$  for an impact parameter  $p$  in units of the half-mass radius  $R_h$  for three different encounter velocities:  $V = 200$  km/s,  $V = 500$  km/s and  $1000$  km/s. The amplitude, of course, depends on the perturber mass and is shown here for 10% of the halo mass but this can

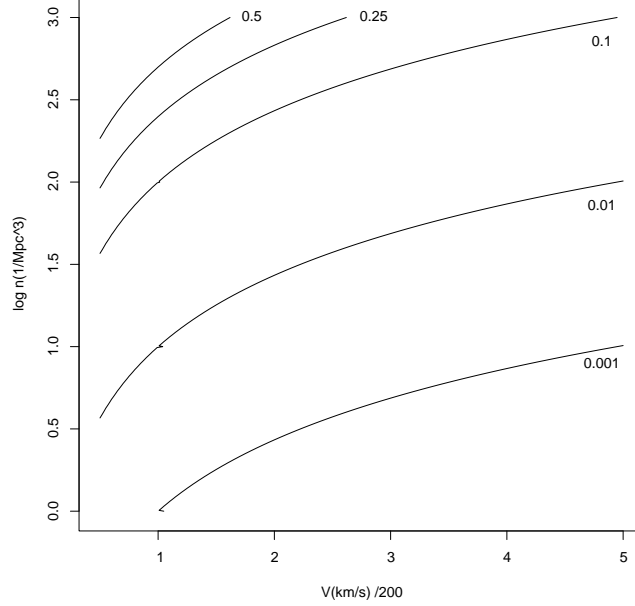


Figure 10. Probability of  $A \geq 0.1$  in the last  $10t_{\text{dyn}}(R_h)$ . The vertical and horizontal axes describe the number density of the environment and relative velocity of encounters.

be scaled to any desired value. For this figure the model adopted for the halo is a  $W_0 = 7$  King model. For example, a perturber with 10% of the halo mass (approximately 3 of an LMC) with pericenter at the halo half-mass radius and encounter velocity of 200 km/s will produce  $A \approx 0.2$ . The lower left panel predicts the displacement between the position of the peak of the density and the position of the center of mass,  $S$ . For the same example, we have  $S \approx 2$  kpc. Of course, this is relative to the unperturbed position and “observed” figure will be a lopsided halo as in Figure 7 (right). Because the halo response is dominated by the modes of the halo rather than properties of the perturber, we expect that the asymmetry should be dominated by contributions at well-defined radii, independent of the perturber parameters. We propose a simple generalization of equation (1) to test this prediction: define  $A(r)$  to be the sums over pixels restricted to those within projected radius  $r$ . The results for wake excited asymmetries are shown in the right-hand-side panels. For a variety of encounter velocities and impact parameters, the profiles of  $A(r)$  are quite similar in shape. n-body simulations of flyby encounters (Vesperini & Weinberg 2000b) have revealed that the radial profile of  $A$  for a disk has a similar shape.

Overall, the values of  $A$  caused by fly-bys range from near zero to  $A \approx 0.2$ . This coincides with range of  $A$  for galaxies in the Medium Deep Survey and in the Hubble Deep Field (Abraham et al. 1996a, 1996b). For a fly-by event, the  $A$  parameter reaches its maximum values when the perturber is close to the pericenter of its orbit but these distortions are sufficiently long-lived that large values of  $A$  may be observed without any close companion in the vicinity of the primary.

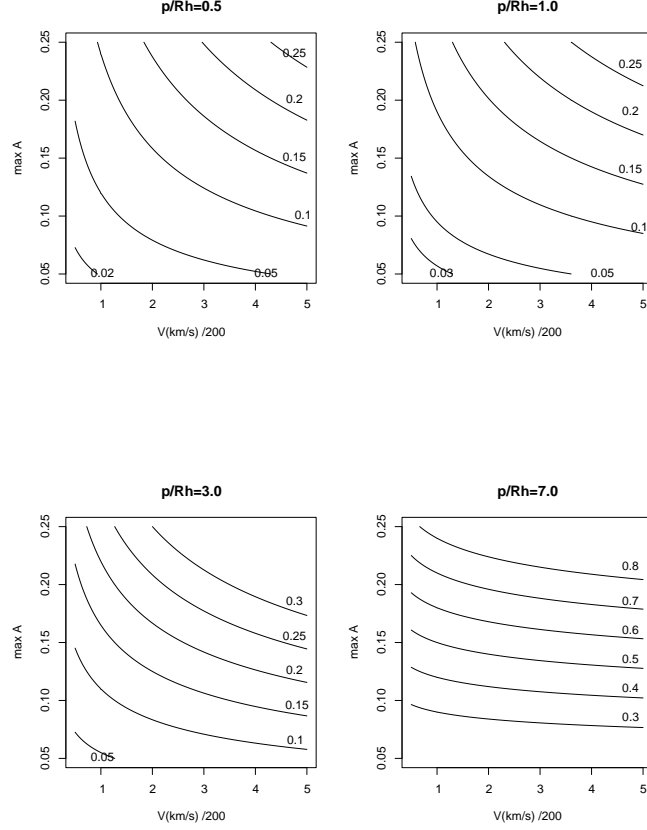


Figure 11. Relative mass (in halo mass units) for the given pericenter to halo half-mass radius ( $p/R_h$ ) to produce  $\max A$  for the encounter velocity  $V$ .

Figures 10 and 11 quantifies the amplitude of  $A$  for in various scenarios. Figure 10 shows curves constant probability for an encounter in the past  $10t_{dyn}(R_h)$  (where  $t_{dyn}(R_h)$  is the dynamical time at the half-mass radius) such that maximum value of  $A$  is greater than 0.1. Since these results are for spherical systems, they apply to either the dark halos of spiral galaxies or elliptical galaxies. Figure 11 provides different look at the same problem. It shows curves constant relative perturber mass necessary to have a maximum value of the asymmetry parameter equal to  $A$  during an encounter with relative velocity  $V$  for a variety of different impact parameters (in units of halo-half mass radii  $p/R_h$ ). Predictions for spiral disks are in progress. In short, a fly-by encounter can result in the observed values for  $A$  and persist for several Gyr (see Vesperini & Weinberg 2000a).

## 5. Summary

In summary, I have attempted to explain how and why both satellite interactions and fly-by encounters can produce large-scale distortions in galaxies of the type commonly observed. Key is the understanding that the shape of large-scale halo and disk modes will be similar regardless of the perturbation source. This is intuitively familiar, I think, from work on spiral density waves from the 1970s. The new twist emphasized here is an analogous dynamical mechanism also leads to global halo modes. Since the halo dominates the mass of the galaxy, it is intimately coupled to the morphology of the luminous disk and spheroid. For example, distortions in any of the components can not be considered independently because all components respond to each other. In particular, satellites, fly-by encounters, and other group interactions can effect a disk by transmission via the halo.

Because the response of a galaxy to a disturbance depends more on the properties of a galaxy than the details of the disturbance, the dynamical mechanisms discussed here predict that galaxy morphology tends to be convergent. In other words there are most likely many paths to similar dynamical response. These considerations lead back to the title: the Milky Way appears to be a typical galaxy showing all manner of asymmetries—lopsidedness, bars, arms, warps—typical of spirals and discussed here as expected from the halo–disk interaction. A detailed theoretical understanding of these interactions will therefore require detailed observations that can only be explored in the Milky Way.

These ideas lead to the possibility that global modes are continuously excited by a wide variety of events such as disrupting dwarfs on decaying orbits, infall of massive high velocity clouds, disk instability and swing amplification and the continuing equilibration of the outer galaxy. The dominant halo modes are low frequency and low harmonic order and therefore can be driven by a wide variety of transient noise sources. Some recent work (Weinberg 2000ab) provides a theory excitation by noise and applies this to the evolution of halos. Preliminary results suggest that noise may drive halos toward approximately self-similar profiles. Additional work will be required to make precise predictions for these trends and explore the consequences for long-term evolution of disks in spiral systems.

Of course, this whole scenario of halo-mediated and halo-driven structure is predicated on the existence of a gravitationally interacting dark halo as opposed to some type of modified gravity. Despite recent papers advancing MOND as a solution as a solution to several theoretical conundrums (e.g. Brada & Milgrom 1999ab, 2000ab), I have not seen a satisfactory description of an evolving Universe without dynamical friction. Dynamical friction is an essential ingredient for hierarchical formation through galaxy merging, and in producing remnant morphology, such as tidal tails. This is quite naturally and consistently explained by dynamical friction which requires gravitational dark matter.

## 6. Future prospects

How does one test this idea that a lively halo is major player to galaxy structure?

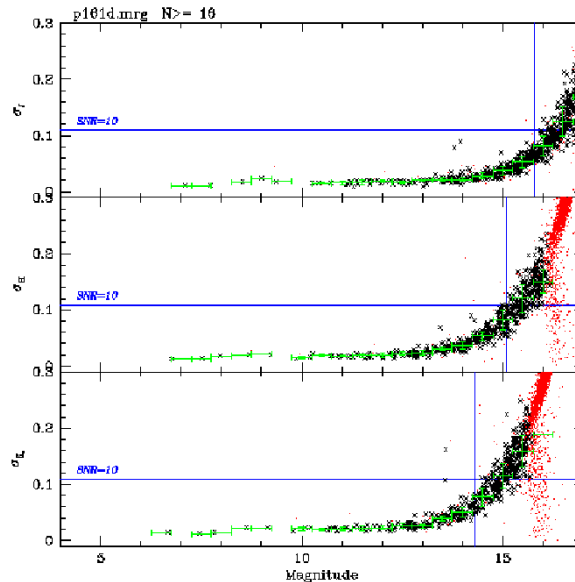


Figure 12. Photometric error estimates for 2MASS point sources in a typical calibration observation. Data for individual sources plotted along with mean and standard error in half-magnitude bins. The crosses are detections in most of the observed frames (reliable) and the dots are detections in only a small number of frames (unreliable). The survey specification is  $S/N=10$  (horizontal lines) at the limits given in the second column of Table 2 (vertical lines). Note that the crossing point varies with seeing and airglow. In general, the survey has exceeded its target. For high  $S/N$ , the standard relative error in each band less than 0.03 mag.

### 6.1. Photometry

2MASS (<http://pegasus.astro.umass.edu>) will catalog approximately 400 million stars ( $S/N = 10$ , cf. Fig. 12) with over 1 billion detections (see Table 2). As of this writing (September 2000) 2MASS has achieved complete full-sky coverage. The intrinsic low-extinction in the near infrared will allow us to probe the Milky Way structure using star counts. Giants, carbon stars and other AGBs are ideal candidates for kinematic follow-up and can be selected based on near-infrared colors. The underlying stellar structure is better represented in the near-infrared than optical bands as discussed in §3. for barred galaxies. In addition to direct photometric detection of asymmetries in both stars and gas, microlensing is already confronting our understanding of inner Galaxy morphology and the dynamics of the LMC. Finally, we can compare with external galaxies. 2MASS galaxy photometry should permit a thorough exploration of asymmetry in the near infrared using diagnostics described in §4.2. as well as more standard Fourier diagnostics.

Table 2. 2MASS point source sensitivity (mag)

Band	Completeness <sup>a</sup>	Detection
J	15.8	17.3
H	15.1	16.6
K <sub>s</sub>	14.3	15.8

<sup>a</sup>at the level  $P = 0.9995$

## 6.2. Kinematics

Most important, I believe, will be prediction of detailed photometric and kinematic signatures. Such a joint inference has been quite important in the last 5–10 years in establishing the existence of the Milky Way bar. In addition to direct radial velocity campaigns, astrometry promises to revolutionize the study of Galactic kinematics. A number of major astrometric missions are in progress or being planned.

The wakes described in the sections above must induce mean flows and we can use n-body simulations of satellite–halo interaction to investigate globally correlated kinematic signatures. For example, Figure 13 shows the deviations from the average tangential velocity for a disk perturbed by a perturber with a mass equal to twice the LMC mass during a fly-by with pericenter at 70 kpc (Vesperini & Weinberg 2000b). We used twice the LMC mass to increase the signal to noise but expect linear scaling with perturber mass. The plot shows the kinematic distortions after the pericenter passage when the perturber is about 200 kpc away from the center of the primary galaxy. The interaction produces mean velocity peaks of 30 km/s in a clear dipole pattern. Similarly, because stars do populate the halo regardless of their origin, we can use halo stars to trace wakes directly. We expect the LMC to produce flows a factor of two smaller. It should be possible to see such a signature at galactrocentric radii of 16 kpc with  $20\mu\text{as}$  precision astrometry (one year baseline). This would require a directed l.o.s. attack with SIM or the full-survey capabilities of GAIA.

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## References

- Abraham, R. G., van den Bergh, S., Glazebrook, K., Ellis, R. S., Santiago, B. X., Surma, P. & Griffiths, R. E. 1996a, *ApJS*, 107, 1
- Abraham, R. G., Tanvir, N. R., Santiago, B. X., Ellis, R. S., Glazebrook, K. & van den Bergh, S. 1996b, *MNRAS*, 279, L47
- Binney, J. 1992, *ARAA*, 30, 51
- Binney, J., and Tremaine, S. 1987, *Galactic Dynamics*, Princeton University Press.
- Blitz, L., Binney, J., Lo, K. Y., Bally, J., and Ho, P. T. P. 1993, *Nature*, 361, 417

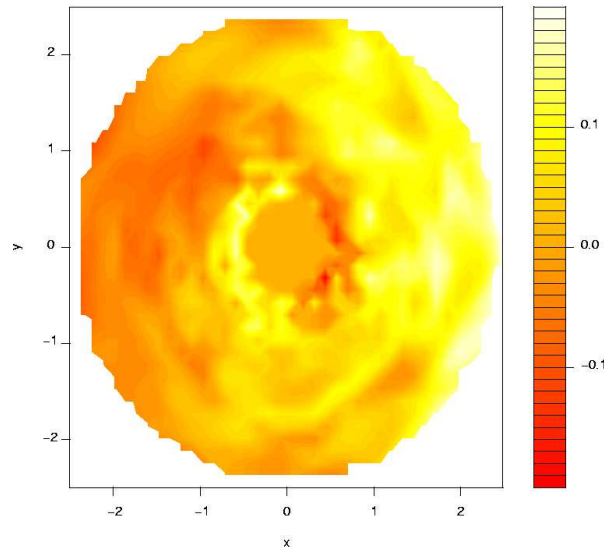


Figure 13. Tangential kinematic signature in disk induced by a fly-by encounter with twice the LMC mass. One length unit is 7 kpc. The center of the galaxy is removed for clarity. The asymmetry in the relative tangential velocity field,  $[\nu_\phi(r, \phi) - \nu_c(r)]/\nu_c(r)$ , is color coded (see key at right).

- Bosma, A. 1991, in *Warped disks and inclined rings around galaxies*, ed. S. Casertano, P. Sackett and F. Briggs, 181
- Brada, R. & Milgrom, M. 1999a, *ApJ*, 512, L17
- Brada, R. & Milgrom, M. 1999b, *ApJ*, 519, 590
- Brada, R. & Milgrom, M. 2000a, *ApJ*, 531, L21
- Brada, R. & Milgrom, M. 2000b, *ApJ*, 541, 556
- Burton W. B. 1998, in G. L. Verschuur, K. I. Kellermann (eds.), *Galactic and Extragalactic Radio Astronomy*, Springer-Verlag, Berlin, p. 295
- Carney, B. W. & Seitzer, P. 1993, *AJ*, 105, 2127
- Chandrasekhar, S. 1969, *Ellipsoidal Figures of Equilibrium*, Yale University Press
- Conselice, C. J., Bershad, M. A., and Jangren, A 2000, *ApJ*, 529, 886
- Debattista, V. P. and Sellwood, J. A. 1998, *ApJ*, 493, L5
- Demleitner, M. 1998, *A&A*, 331, 485
- Djorgovski, S. & Sosin, C. 1989, *ApJ*, 341, L13
- Drimmel, R. Smart, R. L., and Lattanzi, M. G. 1999, preprint (astro-ph/9912398)
- Englmaier, P. & Gerhard, O. 1999, *MNRAS*, 304, 512
- Hofner, P. & Sparke, L. S. 1994, *ApJ*, 428, 466
- Henderson, A. P., Jackson, P. D. and Kerr, F. J 1982, *ApJ*, 263, 116
- Garcia-Ruiz, I., Kuijken, K., Dubinski, J. 2000, preprint, (astro-ph/0002057)

- Hernquist, L. 1990, *ApJ*, 356, 359
- Heyer, M. H., Brunt, C., Snell, R. L., Howe, J. E., Schloerb, F. P. & Carpenter, J. M. 1998, *ApJS*, 115, 241
- Hunter, C., and Toomre, A. 1969, *ApJ*, 155, 747
- Ibata, R., Lewis, G. F., Irwin, M., Totten, E., and Quinn, T. 2000, preprint (astro-ph/0004011)
- Kuijken, K. 1998, *ASP Conf. Ser.* 136: Galactic Halos, 349
- Navarro, J. F., Frenk, C. S. & White, S. D. M. 1997, *ApJ*, 490, 493
- Olling, R. P. and Merrifield, M. R., 2000, *MNRAS*, 311, 361
- Pasha, I. I. & Polyachenko, V. L. 1993, *Astr. Lett.*, 19, 1
- Rudnick, G. & Rix, H. 1998, *AJ*, 116, 1163
- Rudnick, G. Rix, H.-W., and Kennicutt, R. C. Jr. 2000, *ApJ*, 538, 569
- Scalo, J. M. 1987, in *Starbursts and Galaxy Evolution*, ed. T. Thuan, T. Montmerle, and J. Van, Editions Frontieres, p. 445-465
- Sparke, L. S. & Casertano, S. 1988, *MNRAS*, 234, 873
- Tremaine, S. 1993, *AIP Conf. Proc.* 278: Back to the Galaxy, 599
- Weinberg, M. D. 1994, *ApJ*, 421, 481
- Weinberg, M. D. 1998a, *MNRAS*, 297, 101
- Weinberg, M. D. 1998b, *MNRAS*, 299, 499
- Weinberg, M. D. 2000a, preprint (astro-ph/0007275)
- Weinberg, M. D. 2000b, preprint (astro-ph/0007276)
- de Vaucouleurs, G. & Pence, W. D. 1978, *AJ*, 83, 1163
- Vesperini, E. & Weinberg, M. D. 2000a, *ApJ*, 534, 598
- Vesperini, E. and Weinberg, M. D. 2000b, in preparation.
- Zaritsky, D., Smith, R., Frenk, C., and White, S. D. M. 1997, *ApJ*, 478, 39