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A MODEL FOR LOPSIDED GALACTIC DISKS

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ABSTRACT

Many disk galaxies are lopsided; their brightest inner parts are displaced from the center of the outer isophotes or the outer contours of the H I disk. This asymmetry is particularly common in small, low-luminosity galaxies. We argue here that long-lived lopsidedness is a consequence of the disk lying off-center in the potential of the galaxy's extended dark halo and spinning in a sense retrograde to its orbit about the halo center. The stellar velocity field predicted by our gravitational *N*-body simulations is clearly asymmetric.

Subject headings: galaxies: evolution — galaxies: irregular — galaxies: kinematics and dynamics — galaxies: structure

1. INTRODUCTION

Many galaxies display lopsided, rather than bisymmetric, structure, on both large and small scales. *Hubble Space Telescope* observations show that the nuclei of M31 and NGC 4486B do not lie at the center of the bulge isophotes (Lauer et al. 1993, 1996; Davidge et al. 1997). In our own Milky Way, the distribution of molecular gas as measured in CO is offset about 1° in longitude and $+15$ km s^{-1} in velocity from the center (Binney et al. 1991); other mass concentrations in that region also appear to be off-center (Blitz 1995). On kiloparsec scales, many galaxies are asymmetric in both their optical appearance and their gas distribution (see, e.g., Baldwin, Lynden-Bell, & Sancisi 1980). Working from a sample of 1700 spectra, Richter & Sancisi (1994) estimate that about half of all late-type spiral galaxies show clearly asymmetric H I profiles, indicating a lopsided gas disk; about half of this sample are nearby field galaxies, and none lie in rich clusters where interactions between galaxies are frequent. Zaritsky & Rix (1997) estimate that about 50% of spiral galaxies in the field are significantly lopsided at optical and near-infrared wavelengths; the asymmetry involves both young and old stellar populations, and most of their lopsided galaxies lack any obvious companions. Asymmetric bars are particularly common in late-type or small disk galaxies, less luminous than $M_B \sim 18$ (see, e.g., Feitzinger 1980; Odewahn 1996; Matthews & Gallagher 1997). While some lopsidedness in the outer parts of galaxies is undoubtedly caused by recent accretion, the fact that lopsided asymmetries are so common suggests that they can be long-lived.

The origin and persistence of these disk asymmetries remain a mystery. Baldwin et al. (1980) suggest that the lopsided distortions seen in the outer parts of galaxies are kinematic features; in that case they should wind themselves into a leading spiral, since the slow pattern speed $\Omega - \kappa$ is negative. In fact, the one-armed spiral often has the same sense of winding as the two-armed components, which presumably trail (Colin & Athanassoula 1989; Phookun et al. 1992; Phookun, Vogel, & Mundy 1993). The only analytic disk models that are strongly unstable to lopsided distortions are those with many retrograde-streaming particles (Zang & Hohl 1978; Sawamura 1988; Sellwood & Merritt 1994); but observed counterrotation is rare in disk galaxies (see, e.g., Kuijken, Fisher, & Merrifield 1996). Adams, Ruden, & Shu (1989) suggested that a protostellar disk could become unstable to a lopsided distortion; in the galactic context, this would correspond to the stellar disk being off-center in the dark halo. However, Heemskerk, Papaloizou, & Savonije (1992) showed that the $m = 1$ distortion is generally evanescent in the disk, so that resonant growth will not occur. Matthias (1993), investigating orbits in a weakly "egg-shaped" tumbling potential, found that prograde orbits were distorted so as to oppose the "eggness." Miller & Smith (1992) describe an *N*-body simulation of an elliptical galaxy in which a central tilted disk developed, and Taga & Iye (1998) have done simulations in which a massive object wanders away from the center of a dense solar system; but no similar results have been reported in the literature. By contrast, kinematic models for lopsided systems have been quite successful; orbits in the potential of an off-center bar rotating rigidly in an axisymmetric disk can account for the rotation curves of Magellanic barred systems (de Vaucouleurs & Freeman 1973; Christiansen & Jeffreys 1976), while the gas response has a trailing one-armed form (Colin & Athanassoula 1989).

We propose that the key to the puzzling ubiquity of lopsided galactic disks is that they are not dynamically isolated inside the galaxy. Late-type spirals and dwarf galaxies, in which larger scale lopsidedness is most frequently observed, are most likely to be dominated by dark halo mass, see, e.g., Casertano & van Gorkom (1991); Côté, Carignan, & Sancisi (1991); and Broeils (1992a, 1992b). (Athanassoula, Bosma, & Papaoiannou 1987 suggested that in later type galaxies the halo core is larger in relation to the radius of the stellar disk, although this was not confirmed by Broeils 1992a and 1992b.) If a disk found itself off-center in a dominant dark halo with a core of nearly constant density that was large compared with the disk dimensions, most of the disk mass would lie in a region where the angular speed of an orbit about the halo center did not vary strongly. Self-gravity might then act to maintain the disk's coherence as it orbits the center of the halo potential well. This Letter presents our investigation of just such a model using a self-consistent, self-gravitating disk embedded in a static dark halo.

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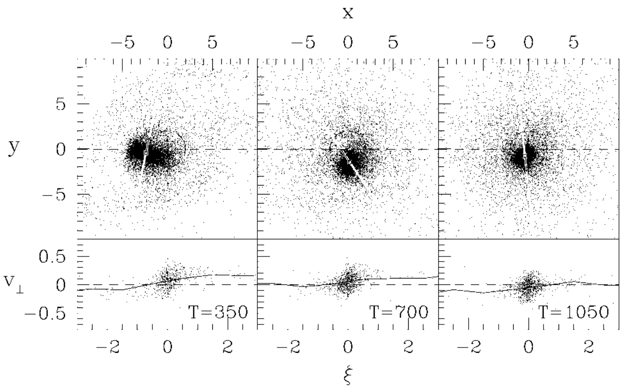

FIG. 1.—(*upper*) Particle positions in a three-dimensional simulation in which the disk started with spin retrograde to its orbit around the halo and its center at $x_0 = 2.5$. The disk particles form a bar that is displaced from the halo center, at the origin; the dashed line marks the halo core $r_c = 2$. (*lower*) Particle velocity normal to a "slit" along the bar minor axis, shown in the upper frames. Distance is measured from the centroid of the most-bound particles (*open square*), in the direction of the arrow.

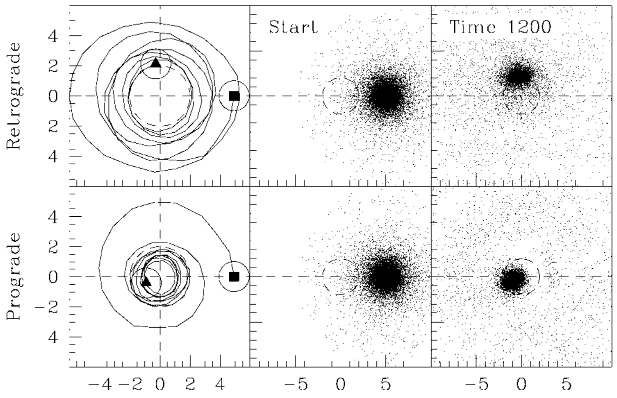

FIG. 2.—Path of the most tightly bound particles, from the start (*square*) to the finish (*triangle*) of a two-dimensional simulation beginning with the disk center at $x_0 = 5$; the solid circles show a radius of 1 disk scale length, and the dashed circle marks the halo core radius $r_c = 2$.

2. GRAVITATIONAL *N*-BODY SIMULATIONS AND RESULTS

We used a tree code (see, e.g., Barnes & Hut 1989) implemented in NEMO (Teuben 1995) to follow the development of a rotating disk that was set up in equilibrium at the center of a fixed "halo" potential, then displaced off-center; every disk particle was also given a "sideways" velocity appropriate to a circular orbit in the halo potential at the radius of the disk center. Our disk was represented by 20,000 particles, distributed in a Kuzmin-Toomre disk (eq. [2-49] of Binney & Tremaine 1987) of unit scale length, which we truncated at $r = 10$. The velocity dispersion in the disk plane was set so that Toomre's (1964) stability parameter $Q = 1.5$; for our three-dimensional simulations, we then "puffed up" the disk by setting the vertical velocity dispersion equal to half that in the radial direction. The halo was of pseudoisothermal form:

$$\rho(r) = \frac{\rho_0}{1 + r^2/r_c^2}. \tag{1}$$

The density $\rho(r)$ is approximately constant within the core radius $r_c = 2$; the speed of a circular orbit in this potential rises linearly in the core, becoming flat at large radii. We took $G = 1$ and chose ρ_0 and the disk density so that the total mass inside $r = 20$ is unity. The halo contributes 90% of this total and accounts for 60% of the mass within 5 disk scale lengths of the center, consistent with the findings of Broeils (1992a, 1992b) for galaxies with $V_{\rm rot} \lesssim 120$ km s^{-1}. The time step Δt was 0.1, and the explicit softening parameter $\epsilon = 0.05$, close to the optimum suggested by the method of Merritt (1996); moderate variations in ϵ made little difference. The opening angle for the tree code was set at 0.75, providing a good balance between resolution and speed.

When the disk spin is retrograde with respect to its orbit around the halo center, we find that the disk remains off-center while making several orbits of the halo. Figure 1 shows a run in which the disk center was initially displaced by $x_0 = 2.5$, so that about 20% of its mass lay at $r_c \lesssim 2$, within the halo core. The velocity dispersion is sufficiently low that the disk formed a bar, which persisted throughout the simulation. Freeman (see de Vaucouleurs & Freeman 1973) proposed a model for Magellanic barred galaxies in which the bar was displaced parallel to its minor axis from the center of a rotating disk; calculations of periodic closed orbits in Freeman's potential showed that the model could reproduce the observed offset between the center of the rotation curve measured in the gas and the bar center. The lower section of Figure 1 shows the "stellar" rotation curve of our model galaxy, as it would be seen by an observer for whom the minor axis of the bar lies in the plane of the sky; the distance ξ is measured from the centroid of the most-bound bar particles. The center of rotation, at $v_\perp = 0$, is displaced from that centroid, and the rotation curve is clearly asymmetric.

When started with a larger displacement, $x_0 = 5$, our retrograde disk drifted inward to $r \gtrsim 2$, just outside the halo core (see Fig. 2). If we gave the disk insufficient angular momentum for a circular orbit in the halo, it first moved inward and then onto a near-circular orbit within the core. The lower portion of Figure 2 is for a disk with prograde rotation, which drifts inward more strongly than one in retrograde orbit; even so, it stays at $r \gtrsim 1$ while making several orbits of the halo. In runs with $r_c = 0.5$, where the core radius of the halo is not large compared with the scale length of the disk, neither the prograde nor the retrograde disk remained far off-center.

3. DISCUSSION

Our experiments imply that a gravitating galactic disk can remain off-center in a halo potential as long as it orbits in a region where the halo has nearly constant density; the effect is more pronounced if the spin of the disk is in the opposite sense to its orbit around the halo center. This behavior can be understood in the limit where the disk dimensions are small and its self-gravity is weak; a particle in a near-circular orbit in the halo then follows an epicycle in a sense retrograde to the orbit. A collection of particles with the same angular momentum, and hence with a common guiding-center radius, would stay together as they orbited the halo center. In the halo core, where the orbital frequency does not vary strongly with radius, the disk's self-gravity can fairly easily maintain coherence in approximately this configuration.

The relatively large fraction of lopsided systems found at redshifts $z \sim 1$, which was apparently a period of rapid galaxy formation (see, e.g., Driver, Windhorst, & Griffiths 1995), suggests that many disks can slowly lose their off-center character as they settle down. In dwarf galaxies, the halo is relatively more massive (Broeils 1992a, 1992b), so lopsidedness is more easily maintained than in more luminous systems. The relation between a lopsided disk and the presence of a central bar has not been studied systematically, but both of these features are characteristic of Magellanic irregular systems. The lopsided Sc galaxy NGC 1637 (Block et al. 1994) appears prominently barred in an infrared image, while at optical wavelengths the bar is hidden by dust and confused by star formation. The spatial scale of the predicted asymmetry is approximately that of the constant-density core; consistent with this idea, the off-center nuclei of M31 and the elliptical NGC 4486B lie within resolved central cores in those galaxies.

Our results are consistent with those of Bontekoe (1988), who investigated the sinking of a satellite galaxy into a larger system. In his unpublished fifth chapter, he reports that the satellite never sank all the way to the center, but the orbit shrank until it enclosed about 10% of the main galaxy's mass. The larger system was represented by a series of polytropes; the more concentrated the polytrope, the closer the satellite sank to its center. Our study also has aspects in common with work on galaxy mergers by Miller & Smith (1995), who found that if two polytropic "cores" orbited each other in isolation, dynamical friction caused them to merge within a couple of orbits. But in the presence of a "halo" of constant density, whether it was represented by a fixed potential or consisted of "live" simulation particles, the cores survived for 15–30 orbits without coming noticeably closer, although the interpretation of the "live halo" model was complicated by an overstable oscillation in the cores' orbital radii. Persistent off-center disks have not been reported in published *N*-body simulations following a galactic disk in an imposed external bulge potential (see, e.g., Sellwood & Wilkinson 1993); but in these computations, the mass distribution of the bulge was in general more concentrated than the disk.

We must be concerned about the effect of dynamical friction on the disk from the particles that would make up a "live" galactic halo. In the context of M31's nucleus, King, Stanford, & Crane (1995) point out that this drag could well be small, if the bulge stars stream rapidly in the same direction as the orbiting cluster's motion. It is unclear even how far the usual estimates of dynamical friction are to be trusted. Bontekoe's (1988) satellite stopped sinking at some distance from the center of the system into which it was accreting. The physical situation of an off-center disk has much in common with that of a rotating bar, where estimates of the drag from the particles of a spherical halo suggest that the bar should rapidly spin down (Weinberg 1985), and gravitational *N*-body experiments also indicate strong braking. But observed galactic bars seem to be fast rotating; Sellwood (1996) summarizes this confusing situation. The long-lived pairs of *counterrotating* bars that develop in the gravitational *N*-body simulations of Sellwood & Merritt (1994) and Friedli (1996) are clearly not discouraged by dynamical friction.

It may well be more useful, instead of calculating only the back-reaction of the halo on the orbiting disk, to look for long-lived modes of oscillation in the combined system. Weinberg (1991, 1994) has developed an analytic method for doing this; examining spherical King models with an isotropic velocity dispersion, he found $m = 1$ modes that, once excited, require many orbital times to decay. The distortions lasted longest in the models in which the core was largest in relation to the total extent of the system. He then used gravitational *N*-body simulations to confirm the existence of these modes. Similar lopsided modes may well exist for a disk within a galactic halo.

We would then expect a relatively long-lived lopsided structure to result when material is accreted so as to push it off-center in the underlying potential. In the central regions of a galaxy, where the gravitational force is provided largely by a "hot" stellar system such as a bulge, an inner disk or nuclear star cluster could remain off-center over many orbital periods. Gas might be captured by a galactic disk so as to push it off-center in the halo; alternatively, accretion of dark matter onto the halo may result in the disk lying off-center. If the orbit of the disk is retrograde with respect to its spin, the lopsidedness is likely to be stronger and more persistent. To maintain appreciable asymmetry, the near constant density halo core should be large enough to encompass a substantial fraction of the disk mass.

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