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INTERNAL ALIGNMENT OF THE HALOS OF DISK GALAXIES IN COSMOLOGICAL HYDRODYNAMIC SIMULATIONS

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ABSTRACT

Seven cosmological hydrodynamic simulations of disk galaxy formation are analyzed to determine the alignment of the disk within the dark matter halo and the internal structure of the halo. We find that the orientation of the outer halo, beyond $\sim 0.1 r_{\rm vir}$, is unaffected by the presence of the disk. In contrast, the inner halo is aligned such that the halo minor axis aligns with the disk axis. The relative orientations of these two regions of the halo are uncorrelated. The alignment of the disk and inner halo appears to take place simultaneously through their joint evolution. The lack of connection between these two regions of the halo should be taken into account when modeling tidal streams in the halos of disk galaxies and when calculating intrinsic alignments of disk galaxies based on the properties of dark matter halos.

Subject headings: dark matter — galaxies: evolution — galaxies: formation — galaxies: halos — galaxies: spiral

Online material: color figures

1. INTRODUCTION

The alignment of galactic disks within their triaxial dark matter halos is both observationally and theoretically difficult to determine. Observationally, dark matter can only be traced by its gravitational effect on luminous matter. Efforts to determine the shapes of individual dark matter halos around disk galaxies usually rely on the motions of tidal streams (Johnston et al. 1999, 2005; Ibata et al. 2001, 2004; Helmi 2004a, 2004b; Martínez-Delgado et al. 2004; Law et al. 2005), polar rings (Sackett et al. 1994), or the flaring of the gas layer (Olling & Merrifield 2000). Most of these studies have found that the halo is flattened along the pole of the galactic disk; however, the degree of flattening for even the best-studied case of the Milky Way is controversial, with values ranging from 0.8 to 1.7 (i.e., *elongated* along the Galactic pole).

Theoretical determinations of galactic disk alignment within halos have been restricted by available computing power. *N*-body simulations have been used to determine the flattening and internal alignment of pure dark matter halos (Barnes & Efstathiou 1987; Warren et al. 1992; Jing & Suto 2002; Bailin & Steinmetz 2005, hereafter BS05). These studies have found that the axes of halos, especially the minor axes, are very well aligned internally; the halo is well approximated by a set of concentric ellipsoids. Under the assumption that the angular momentum of the baryons that form the disk is aligned with the angular momentum of the dark matter, the disk axis is expected to lie typically 25° from the halo minor axis (BS05). However, hydrodynamic simulations suggest that the angular momentum of the baryons and dark matter are not perfectly aligned (van den Bosch et al. 2002; Sharma & Steinmetz 2005). Moreover, the orientation of the halo may change in the presence of a misaligned disk (Binney et al. 1998, hereafter BJD98).

This problem can now be addressed with recent high-resolution simulations of disk galaxy formation. These simulations have traditionally formed disks that are much more compact than observed galactic disks (Navarro & Steinmetz 1997). However, modern treatments of feedback and more consistent analyses of the simulations and observations have led to much better agreement: the physical size of the disks is realistically reproduced, and the lack of angular momentum manifests itself primarily in a very pronounced, slowly rotating bulge-halo component (Abadi et al. 2003). Recent works employing advanced multiphase descriptions of the interstellar medium reduce the dominance of the bulge, in particular if feedback from active galactic nuclei is included (Robertson et al. 2004; Okamoto et al. 2005). Since the physical size of the disks is realistically reproduced and since the location of the surrounding matter that provides the tidal torque is unaffected, the orientation of the angular momentum, and therefore the disk, is expected to be robust.

Navarro et al. (2004) found that in four such simulations, the disk axis tends to lie within 30° of the intermediate axis of the large-scale mass distribution at turnaround, indicating that primordial tidal torques play an important role in determining the final disk orientation. It is known that the radial distribution of dark matter in the halo changes in the presence of cooled baryons (Gnedin et al. 2004), and therefore it is likely that other properties of the matter distribution are affected too. Kazantzidis et al. (2004, hereafter K04) studied the change in the axes of the halo of a high-resolution disk galaxy simulation compared with the *N*-body case. They found that the axis ratios of the halo were dramatically higher (i.e., more spherical) when the simulation included baryon cooling than when the baryons were not present or not allowed to cool to a disk. They also found that the minor axis of the halo was aligned with the disk axis within $r < 0.2 r_{180}$, but that the halo became *elongated* along the disk axis beyond that radius.

The alignment of disks with their dark matter halos is important for understanding a number of unresolved questions

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TABLE 1
Properties of the Simulations

Simulation Name (1)	Code (2)	M_{vir} ($M_\odot$) (3)	r_{vir} (kpc) (4)	r_{disk} (kpc) (5)
KGCD	GCD+	8.8×10^{11}	240	10
AGCD	GCD+	9.3×10^{11}	270	21
AGSPH	GRAPESPH	9.4×10^{11}	270	23
KIA5	GRAPESPH	1.7×10^{12}	300	4
KIA9	GRAPESPH	2.1×10^{12}	320	20
KIB1	GRAPESPH	2.9×10^{12}	390	16
KIB2	GRAPESPH	8.5×10^{11}	260	5

regarding disk galaxy formation, evolution, and dynamics. Warps in disk galaxies are ubiquitous (Reshetnikov & Combes 1998; Schwarzkopf & Dettmar 2001; García-Ruiz et al. 2002) and have been proposed to be caused by misalignment between the disk and the dark matter halo (Dekel & Shlosman 1983; Toomre 1983; Bailin 2004; but see Nelson & Tremaine 1995; BJD98). This possibility can be ruled out if such misalignments never occur in fully self-consistent simulations of disk galaxy formation. The Holmberg effect (Holmberg 1974; Zaritsky et al. 1997; but see Brainerd 2004; Willman et al. 2004) may be explained if galactic disks preferentially lie perpendicular to the major axis of their dark matter halo (Knebe et al. 2004; Zentner et al. 2005). Models of the Sagittarius tidal stream cannot simultaneously fit the leading and trailing arms of the stream with the same halo flattening (Helmi 2004b; Law et al. 2005); a more detailed understanding of the relationship between the location of the disk and the shape of the dark matter halo may be necessary to resolve this issue. Finally, the intrinsic alignment of observed galaxies acts as a background contaminant in weak-lensing studies. Predictions of the magnitude of this effect based on linear theory or *N*-body simulations must assume a disk orientation for each halo, which is as yet untested (Heavens et al. 2000; Pen et al. 2000; Crittenden et al. 2001).

In this Letter, we analyze the shape and internal alignment of the dark matter halos of seven high-resolution cosmological disk galaxy formation simulations and discuss the possible observational effects of such internal structure.

2. METHODOLOGY

We analyze seven cosmological simulations that use the multi-mass technique to self-consistently model the large-scale tidal field while simulating the galactic disk at high resolution. These simulations include self-consistently almost all the important physical processes in galaxy formation, such as self-gravity, hydrodynamics, radiative cooling, star formation, supernova feedback, and metal enrichment.

The properties of the simulations are listed in Table 1. Column (1) contains the name by which we refer to each simulation, column (2) is the code used to run the simulation, column (3) is the virial mass of the galaxy, column (4) is the virial radius of the galaxy, and column (5) contains the radial extent of the gas disk in each simulation, defined as the largest radius at which we find gas particles in the disk plane. The primary simulation we analyze is the "KGCD" simulation, performed using the GCD+ code (Kawata & Gibson 2003). The simulation is a higher resolution model of galaxy "D1" in Kawata et al. (2004). The mass and softening length of individual gas (dark matter) particles in the highest-resolution region are 9.2×10^5 (6.2×10^6) $M_\odot$ and 0.57 (1.1) kpc, respectively. We analyze the KGCD simulation at both the final output at $z = 0.10$ and an output at $z = 0.37$ (approximately 2.2 Gyr earlier)

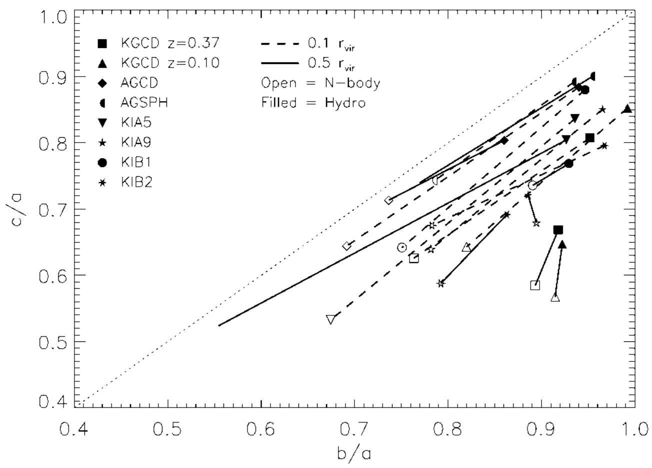

Fig. 1.—Axis ratios *b*/*a* and *c*/*a* of the dark matter halos in simulations including baryonic physics, compared with simulations containing only dark matter. Dashed lines and attached symbols represent the axes measured at $0.1r_{vir}$, while solid lines and attached symbols represent the axes measured at $0.5r_{vir}$. Filled symbols represent the simulations containing baryonic disks, while open symbols represent the *N*-body–only simulations. Lines connect simulations with the same initial conditions and show the change in axis ratio induced by the inclusion of baryonic physics. The different symbols refer to the different simulations. [*See the electronic edition of the Journal for a color version of this figure.*]

at which the disk first appears fully formed in approximately its final state to determine whether there is significant evolution in the halo structure in the absence of major mergers. In order to ensure that our results are not particular to this code, the feedback prescription, or the particular set of initial conditions, we also analyze the final snapshot of the simulation described in Abadi et al. (2003; "AGSPH"), a simulation with the same initial conditions as AGSPH but run using GCD+ ("AGCD"), and four additional GRAPESPH (Steinmetz 1996) simulations: KIA5, KIA9, KIB1, and KIB2. Dark matter–only versions of each of these simulations were also run in order to directly compare the alignment of each halo with and without a galactic disk.

The principal axes and axis ratios of the dark matter halo are calculated using the method of BS05. Briefly, the particles are split into spherical shells bounded by radii of $r = (0.025, 0.05, 0.1, 0.25, 0.5, 1.0)r_{vir}$.[10] The reduced inertia tensor is calculated for the particles within each shell and diagonalized to determine the principal axes. Finally, the axis ratios determined from the eigenvalues of the reduced inertia tensor are corrected for the bias introduced by using spherical shells. In this way, the results at each radius are entirely independent (K04).

3. RESULTS

The change in axis ratio for our simulations is shown in Figure 1. An increase in sphericity is clearly evident in this figure, with a magnitude that decreases at larger radii. The magnitude of this change is smaller than that found by K04, who also found that the presence of baryonic cooling dramatically increases the axis ratios of dark matter halos, with changes in *b*/*a* and *c*/*a* that range from 0.35 at small radii to zero at the virial radius. The change in axis ratios was particularly evident in their galactic disk simulation, where *b*/*a* rose by almost 0.6 when a galactic disk was present. This difference

[10] We use the fitting function from Appendix A of Kitayama & Suto (1996) to calculate the overdensity that defines the virial radius r_{vir} as a function of cosmology and *z*.

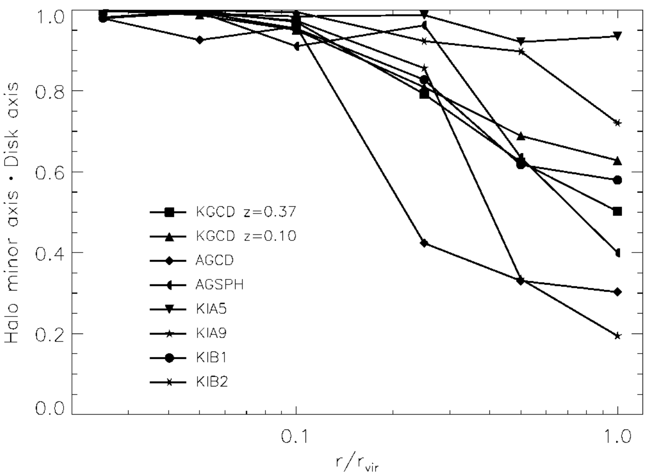

FIG. 2.—Alignment between the minor axis of the dark matter halo at different radii and the disk axis. The different symbols represent different simulations. [*See the electronic edition of the Journal for a color version of this figure.*]

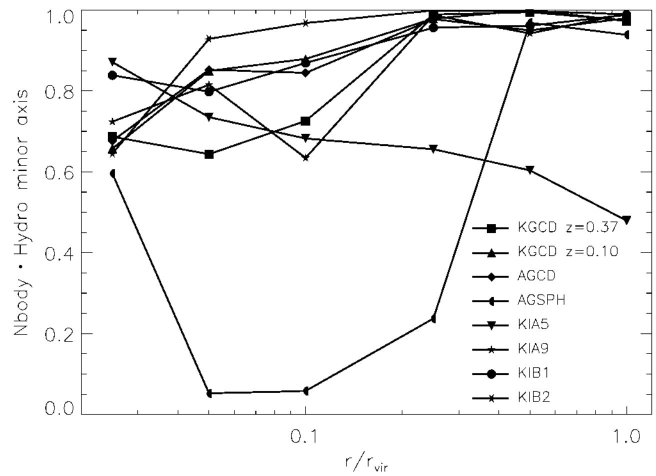

FIG. 3.—Alignment between the minor axis of the dark matter halo of each hydrodynamic simulation and of the matching *N*-body simulation, as a function of radius within the halo. The different symbols represent different simulations. [*See the electronic edition of the Journal for a color version of this figure.*]

in magnitude may simply be small number statistics: the *N*-body version of the galactic disk simulation of K04 is exceptionally flattened, and therefore a much greater increase in axis ratio is possible.

The direction cosine between the disk axis and the halo minor axis at each radius is shown in Figure 2, while Figure 3 shows the change in the alignment of the minor axis at each radius compared with the dark matter–only version of the same simulation. This is unity if the axes are perfectly aligned and vanishes if they are perpendicular. The disk axis is defined to be the minor axis of the gas distribution within $r_{\rm disk}$; in all cases, this matches the axis determined by visual inspection and that determined including all baryons within $r_{\rm disk}$. Two regimes are clearly visible in Figures 2 and 3:

1. $r < 0.1 r_{\rm vir}$.—In the inner regions of the halo, the minor axis is extremely well aligned with the disk axis.
2. $r > 0.1 r_{\rm vir}$.—In the outer regions of the halo, the orientation of the minor axis is unchanged from the *N*-body–only case.

The transition between these regimes occurs at a slightly larger radius in the AGSPH and KIA5 simulations; as these simulations contain respectively the largest and smallest disks, the transition radius does not appear to depend on the disk radius.

KIA5 appears as an outlier on all these plots: it has a large change in axis ratio even at large radius, it shows very little change in orientation between the inner and outer halo, and the minor axis in the hydrodynamic simulation is not at all aligned with the *N*-body case. This latter point may be because the *N*-body version of KIA5 is exceptionally prolate in its outer regions, making a determination of the minor axis ill-defined. However, we note that KIA5 contains the smallest gaseous disk and may represent an earlier-type galaxy than the other simulations, with a disk that is much less important to its dynamics. This interpretation is bolstered by the fact that KIB2, which contains the second-smallest disk after KIA5, also shows smaller than average misalignment between its inner and outer regions.

The distribution of cosines between randomly oriented unit vectors is uniform with a mean of 0.5. This is precisely the distribution of cosines between the inner and outer halo axes in Figure 2. Therefore, we conclude that the orientations of the inner and outer halo in simulations containing galactic disks are uncorrelated. In contrast, the minor axes of pure dark matter halos are very well aligned throughout their entire extent, with a direction cosine of always greater than 0.88 (see Fig. 8*b* of BS05). Therefore, the presence of the disk strongly modifies the shape of the inner halo, reorienting it so that the halo minor axis aligns with the disk axis. This is in qualitative agreement with BJD98, who discussed the effect of misalignment on the disk rather than the halo but concluded that the halo reorients itself to line up with the disk axis. The results for the KGCD simulation at $z = 0.10$ and $z = 0.37$ are very similar, indicating that either this reorientation must happen on a short timescale or the processes that determine the disk and halo axes act on both simultaneously during their formation.

There is some relation between the disk axis and the minor axis of the unperturbed halo, as the distribution of innermost points in Figure 3 has a mean greater than 0.5; this is expected as a result of the tendency of the halo angular momentum to align with its minor axis (Warren et al. 1992; BS05). However, this correlation is not strong, and the slight misalignment within pure dark matter halos ensures that there is no residual correlation between the inner and outer regions of halos containing disks.

4. DISCUSSION

The final orientation of the galactic disk in a cosmological dark matter halo is still unresolved. It is clearly related to the angular momentum of the material in the halo, and the results of Navarro et al. (2004) indicate that the primordial tidal torques of the large-scale matter distribution play an important role, but there is considerable galaxy-to-galaxy variation in the results of the simulations. While the primordial tidal torques generate the angular momentum in the material that eventually becomes the disk, the accretion of this material by the disk is a clumpy, stochastic process (Vitvitska et al. 2002), and therefore we are not able to predict the precise orientation of the disk.

However, the results presented in § 3 clearly indicate that the halo orientation within $0.1 r_{\rm vir}$ matches the disk axis. Beyond $0.1 r_{\rm vir}$, the halo orientation is unaffected by the presence of the disk, although the axis ratios are somewhat larger (K04). This outer region is itself internally well aligned, resulting in two distinct regions of the halo with unique and uncorrelated orientations. These results are independent of the time that the halo is studied, the code used, and the particular galaxy simulated.

It is interesting to consider whether the disk drives the orientation of the inner halo or vice versa. While the disk is less massive than the inner halo (the baryons represent 15%–42% of the mass within $0.1r_{vir}$), it is also much more flattened than the halo. To evaluate which is most important, we have constructed rings of test particles tilted by 10° with respect to the disk plane and compared the gravitational torque on these test particles due to the dark matter with that due to the baryons. For rings of radius less than $\sim 0.1r_{vir}$, that is, in the aligned region, the torques from the dark matter and baryons are of comparable magnitude, while the dark halo dominates the torque at larger radii. Therefore, it appears that the alignment is due to the simultaneous evolution of the disk and halo rather than the disk directly driving the halo orientation or vice versa.

If the structure of the stellar halo is determined by the dark halo, we may expect the properties of the stellar halo to change abruptly at $0.1r_{vir}$. In fact, the flattening of the stellar halo of the Milky Way changes from a flattened distribution aligned with the disk at $R < 15$ kpc to an essentially spherical distribution at $R \approx 20$ kpc (Chiba & Beers 2000). This spherical distribution may be an intermediate stage between two misaligned flattened regions. However, the virial radius of the Milky Way is likely at least 250 kpc, indicating that this observed transition occurs at a smaller radius than the transition seen in our simulated halos.

Because the disk is always aligned with the halo in the inner regions, general misalignment between the disk and halo is not a viable mechanism for generating galactic warps. However, if very low surface density disk material exists beyond $0.1r_{vir}$, it may settle into the outer halo symmetry plane and therefore be warped with respect to the inner disk. Indeed, BJD98 suggested that the warp modes within live halos would be essentially different from those in static halos not in the configuration of the disk, but rather in the configuration of the halo. However, the outer extent of the baryonic disk is determined by the material that has most recently cooled; this material is essentially unaffected by the angular momentum problem (Navarro & Steinmetz 1997). Therefore, the maximum extent of simulated disks is expected to be accurate, and therefore the disk is unlikely to extend into the misaligned outer halo. However, simulations of such systems should be carried out to determine if such warped configurations are stable, and to determine how the surface density of the disk affects the tendency of the halo to realign itself.

The solution to the Holmberg effect proposed by Knebe et al. (2004) requires that galactic disks be preferentially perpendicular to the major axis of the halo. However, we find that the orientation of the disk is uncorrelated with the orientation of the major axis of the outer halo, where most satellite galaxies lie, casting doubt on this hypothesis.

Finally, we note that the orbit of the Sagittarius dwarf spheroidal in the Milky Way contains segments both inside and outside of $0.1r_{vir}$ (see, e.g., Helmi & White 2001). If the orientation of the outer Milky Way halo is significantly different from the orientation of the Galactic disk, as suggested by our results, then the orbits of particles in the Sagittarius stream may differ from those calculated assuming that the halo can be approximated by concentric ellipsoids (note however that the stream depends on the flattening and orientation of isopotential contours, which are generated by matter at a range of radii and therefore change more smoothly than the density). This additional ingredient may be required in order to self-consistently model both the leading and trailing arms of the stream.

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