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COLD DARK MATTER SUBSTRUCTURE AND GALACTIC DISKS I: MORPHOLOGICAL SIGNATURES OF HIERARCHICAL SATELLITE ACCRETION

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ABSTRACT

We conduct a series of high-resolution, fully self-consistent dissipationless N-body simulations to investigate the cumulative effect of substructure mergers onto thin disk galaxies in the context of the ΛCDM paradigm of structure formation. Our simulation campaign is based on a hybrid approach combining cosmological simulations and controlled numerical experiments. Substructure mass functions, orbital distributions, internal structures, and accretion times are culled directly from cosmological simulations of galaxy-sized cold dark matter (CDM) halos. We demonstrate that accretions of massive subhalos onto the central regions of host halos, where the galactic disk resides, since $z \sim 1$ should be common occurrences. In contrast, extremely few satellites in present-day CDM halos are likely to have a significant impact on the disk structure. This is due to the fact that massive subhalos with small orbital pericenters that are most capable of strongly perturbing the disk become either tidally disrupted or suffer substantial mass loss prior to $z = 0$. One host halo merger history is subsequently used to seed controlled N-body experiments of repeated satellite impacts on an initially-thin Milky Way-type disk galaxy. These simulations track the effects of six dark matter substructures, with initial masses in the range $\sim (0.7-2) \times 10^{10} M_{\odot}$ ($\sim 20-60\%$ of the disk mass), crossing the disk in the past ~ 8 Gyr. We show that these accretion events produce several distinctive observational signatures in the stellar disk including: a long-lived, low-surface brightness, ring-like feature in the outskirts; a significant flare; a central bar; and faint filamentary structures that (spuriously) resemble tidal streams in configuration space. The final distribution of disk stars exhibits a complex vertical structure that is well-described by a standard "thin-thick" disk decomposition, where the "thick" disk component has emerged primarily as a result of the interaction with the most massive subhalo. We conclude that satellite-disk encounters of the kind expected in ΛCDM models can induce morphological features in galactic disks that are similar to those being discovered in the Milky Way, M31, and in other nearby and distant disk galaxies. These results highlight the significant role of CDM substructure in setting the structure of disk galaxies and driving galaxy evolution. Upcoming galactic structure surveys and astrometric satellites may be able to distinguish between competing cosmological models by testing whether the detailed structure of galactic disks is as excited as predicted by the CDM paradigm.

Subject headings: cosmology: theory — dark matter — galaxies: formation galaxies: dynamics — galaxies: structure — methods: numerical

1. INTRODUCTION

In the cold dark matter (CDM) paradigm of structure formation, galaxy-sized dark matter halos form via the continuous accretion of smaller systems (e.g., Blumenthal et al. 1984). Recently, an explosion of data has disclosed unexpected kinematic and structural complexity in the Milky Way (MW), its neighbors, and distant galaxies. There is a growing body of evidence from local star-count surveys that the MW has, in fact, experienced numerous accretion events. Since the original discovery of the Sagittarius dwarf galaxy and its associated tidal stream (Ibata et al. 1994; Yanny et al. 2000; Ivezić et al. 2000; Ibata et al. 2001c,b; Majewski et al. 2003), at least 5 additional, spatially-coherent structures have been found in and around the MW (Newberg et al. 2002; Gilmore et al. 2002; Yanny et al. 2003; Martin et al. 2004; Juric et al. 2005; Martínez-Delgado et al. 2005; Grillmair 2006a,b; Grillmair & Dionatos 2006; Rocha-Pinto et al. 2006; Belokurov et al. 2006). These numbers are in general agreement with predictions of dwarf galaxy accretion and disruption in the prevailing ΛCDM cosmological model (Bullock et al. 2001; Bullock & Johnston 2005; Bell et al. 2007) and the character of the structures themselves are similar to those expected in simulations of satellite galaxy disruption (Johnston et al. 1995).

Among the more intriguing stellar structures discovered in the MW is the Monoceros Ring (Newberg et al. 2002). This coherent, low-metallicity feature spans $\sim 170°$ degrees around the Galaxy and lies near the disk plane at a Galacto-centric distance of ~ 20 kpc (Newberg et al. 2002; Yanny et al. 2003; Ibata et al. 2003; Rocha-Pinto et al. 2003; Conn et al. 2005). It is unclear whether this structure is yet another example of tidal debris from an accreted dwarf galaxy (Yanny et al. 2003; Ibata et al. 2003; Helmi et al. 2003; Martin et al. 2004; Peñarrubia et al. 2005)

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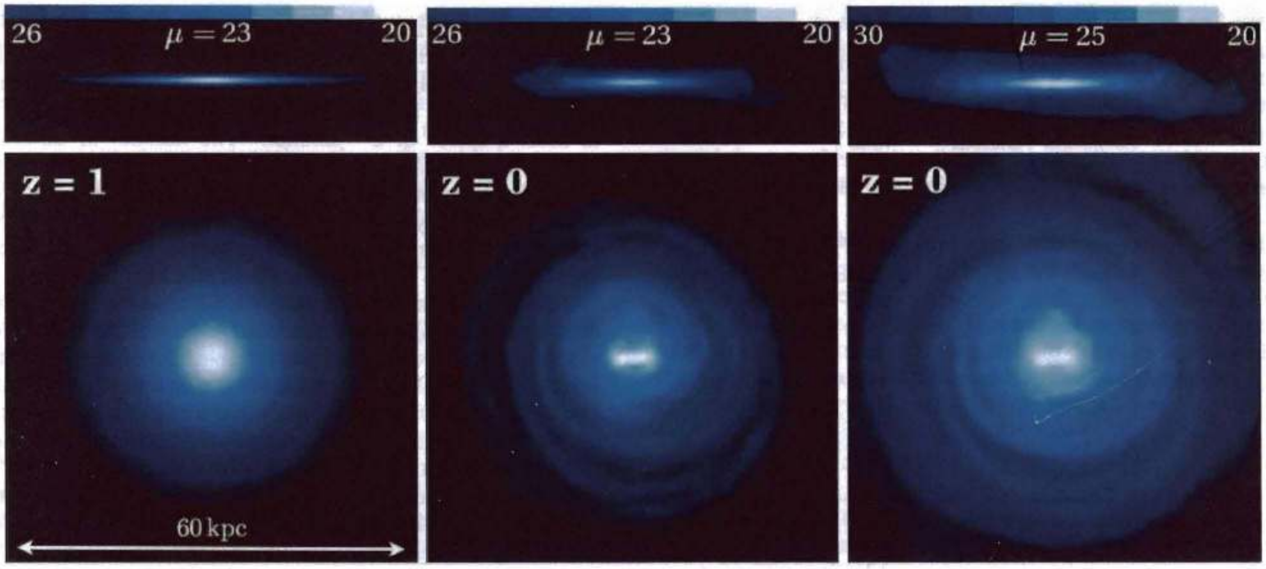

FIG. 3.— Surface brightness maps of disk stars in the simulated accretion history of host halo G_1. The edge-on (*upper panels*) and face-on (*bottom panels*) views of the disk are displayed in each frame and the color bar in each upper panel indicates the surface brightness limits used to generate the maps. In constructing these images, a stellar mass-to-light ratio equal to $M_*/L = 3$ is assumed. Bottom images are 60 kpc on a side, while top images measure 18 kpc by 60 kpc. The *left* panel shows the initial disk assuming that the sequence of satellite-disk interactions initiates at $z = 1$. The *middle* and *right* panels depict the disk after the last satellite passage, evolved in isolation for additional ~ 4 Gyr, so that the evolution of disk stars is followed from $z = 1$ to $z = 0$. In the left and middle panels, images are shown to a limit of $\mu = 26$ mag arcsec^{-2}, while the right panel corresponds to a "deeper" surface brightness threshold of $\mu = 30$ mag arcsec^{-2}. Results are presented after centering the disk to its center of mass and rotating it to a new coordinate frame defined by the three principal axes of the total disk inertia tensor. Considerable flaring and a wealth of features that they might falsely be identified as tidal streams can be seen in the perturbed disk down to $26-30$ mag arcsec^{-2}. The existence of non-axisymmetric structures such as extended outer rings and bars after a significant amount of time subsequent to the last accretion event confirm their robustness and indicate that axisymmetry in the disk has been destroyed and is not restored at late times.

Finally, we stress that prior to commencing the satellite-disk encounter simulations, the primary galaxy model was tilted so that the disk angular momentum vector was aligned with the angular momentum of the host CDM halo G_1. This choice is motivated by results of cosmological simulations suggesting that the angular momenta of galaxies and their host halos tend to be well aligned (e.g., Libeskind et al. 2007).

3. RESULTS

In this section we present results regarding the evolution of an initially-thin stellar disk subject to a cosmologically-motivated subhalo merger history. Recall that we examine the disk response to substructure impacts S1-S6, which are designed to mimic a reasonable *central* accretion history for a MW-sized halo over the past ~ 8 Gyr. The "final" disk discussed in the next sections has experienced the S1-S6 encounters and was evolved in isolation for ~ 4 Gyr after the last interaction. While this allows for relaxation after the encounters, it also ensures that all of the resultant morphological features are long-lived rather than transient. Consequently, our results are relevant to systems that exhibit no obvious, ongoing encounters and have been allowed to relax in isolation.

We compute all properties of the disk and show all visualizations of the disk morphology after centering the disk to its center of mass and rotating it to a new coordinate frame defined by the three principal axes of the total disk inertia tensor. The motivation behind performing both actions is twofold. As discussed in more detail in Paper II, exchange of angular momentum between the infalling satellites and the disk tilt the disk plane substantially over the merging history and cause the disk center of mass to drift from its initial position at the origin of the coordinate frame. In the original coordinate frame, rotation in a tilted disk would appear as vertical motion interfering with the interpretation of the results.

Finally, we underscore that there is nothing exceptional about host halo G_1 as far as the properties of the subhalo populations are concerned. In all other three MW-sized halos we analyzed, substructures of similar numbers, masses, internal structures, orbital parameters, and accretion times were identified. Though our simulation program is designed to mimic the activity in the inner halo of G_1, the similarity of subhalo populations in all four halos suggests that the results presented next should be regarded as fairly general.

3.1. *Global Disk Morphology*

Figure 3 depicts the evolution of the global structure of a thin stellar disk that experiences a merging history of the type expected in ΛCDM. The left panel shows the initial configuration of disk stars assuming that the sequence of satellite-disk interactions initiates at $z = 1$, while the right and middle panels show the final configuration at $z = 0$ *of the same stars* at two different surface brightness thresholds. Stellar particles are color-coded by the projected *surface brightness*. In producing these images, we have assumed a stellar mass-to-light ratio of $M_*/L = 3$ in the V-band, as would be appropriate for an old stellar population with colors relevant for thick disks (Dalcanton & Bernstein 2002). This particular choice produces a peak edge-on central surface brightness of $\mu \sim 21$ mag arcsec^{-2}, similar to values seen in optical surveys of nearby, edge-on, undisturbed disk galaxies (Yoachim & Dalcanton 2006). A different choice for M_*/L would simply result in a dimming or brightening of these images and subsequent figures accordingly.

Several interesting morphological signatures of satellite-disk interactions are clear from these images. First, a wealth