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DYNAMICS OF DISK GALAXIES AND THEIR SATELLITES

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RESUMEN

Estudiamos el calentamiento y sobrevivencia de los discos galácticos a la acreción de satélites a través de simulaciones autoconsistentes de N-cuerpos. Se consideran satélites con varias estructuras internas como también órbitas de diferentes excentricidades y orientaciones. Además, se estudia el papel que desempeña la región central (a través del bulbo) de la galaxia. Encontramos que los resultados analíticos de Tóth & Ostriker (1992) sobrestiman el calentamiento y enzanchamiento del disco por un factor de $2-3$. En particular, se encuentra que los discos son más robustos a la acreción de satélites masivos ($M_S \sim 0.2\,M_D$) que siguen órbitas retrógradas. Finalmente, la importancia de la respuesta del halo es analizada.

ABSTRACT

We address the heating and survival of galaxy disks by infalling satellites using self-consistent N-body simulations. We consider satellites with a variety of internal structures as well several orbits with different eccentricities and orientations. Also, the role of the central region of the galaxy (through a bulge) is studied. We found that the analytical results of Tóth & Ostriker (1992) overestimate the heating and thickening of the disk by a factor of $2-3$. In particular, we found disks are more robust to the accretion of massive satellites ($M_S \sim 0.2\,M_D$) that follow retrograte orbits. Finally, the importance of the responsiveness of the halo is analized.

Key Words: **GALAXY: KINEMATICS, DYNAMICS AND EVOLUTION — GALAXIES: STRUCTURE — METHODS: NUMERICAL**

1. INTRODUCTION

One of the major challenges for CDM models is to explain the existence of spiral galaxies. On one hand, galaxy disks are fragile systems characterized by being cold (i.e., rotationally supported with ratios of $V_{rot}/\sigma \sim 8$) and thin (with a scale ratio of $z_D/R_D \sim 0.1-0.2$). On the other hand, in CDM models structure growths hierarquically from the smaller systems to larger ones through minor and major mergers. So, it is expected that galaxy disks are subject to strong perturbations coming from the accretion process during the formation of the halo.

Based in these facts, Tóth & Ostriker (1992) derived a restrictive constraint about the infalling material that a galaxy can accrete without produce a substantial damage to the disk. They argued that in a high density CDM Universe about 80% of the dark haloes have grew in mass by 10% or more during the last 5 billion years which can cause severe disruptive effects on galaxy disks. They estimated that for a typical disk galaxy like the Milky Way no more than 4% of its present mass inside the solar radius could have been accreted since the formation of the solar system in order to be compatible with the observed values of Toomre's stability Q-parameter and disk scaleheight.

Two approaches have been assumed to address the fragility of galaxy disks: (1) by studying the later stages of the accretion process (Quinn & Goodman 1985; Quinn, Hernquist, & Fullagar 1993; Walker, Mihos, &

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Hernquist 1996; Huan & Carlberg 1997; hereafter QG, QHF, WMH and HC, respectively). The most recent works by WMH and HC included a key element: the responsiveness of the halo to the accretion process. However, a possible weakness of these last studies is that the satellites are in nearly circular orbits. In the case of WMH the satellite is already within 21 kpc from the galaxy center and, in the case of HC the satellites are almost distroyed before they interact strongly with the disk. The present work is a continuation and extension of this line of investigation. (2) The second approach is trying to determine the accretion rate of satellites onto dark haloes as a function of their mass and orbital parameters. These estimates are based in the Press-Schecter formalism for hierarchical clustering (Lacey & Cole 1993). Also, in this cosmological context, high resolution simulations have been carried out by Navarro, Frenk, & White (1994, 1995). In particular, Navarro et al. (1995) have found that fewer than 30% of the disks grew by more than 10% in the last 5 billion years while about 80% of the dark haloes grew this amount or more so. In this way, a $\Omega = 1$ CDM universe may be reconciled with galaxy disks. We should notice that despite these simulations provides useful indication about the accretion rates of infalling satellites they do not have enough resolution to provide information about how these events perturb galaxy disks.

In this paper follows the first approach but using the information given by high resolution simulations such as the distribution of eccentricities for the orbits of the satellites. In the following section we briefly describe the numerical methods used to this end as well as our main results.

2. NUMERICAL MODELS

We summarize the adopted models, the method to follow the evolution of the system and the orbital parameters for our simulations.

2.1. *Galaxy and Satellite Models*

We use a self-consistent three-component model as the one described by Hernquist (1993). The disk is given by

$$\rho_D = \frac{M_D}{4\pi R_D^2 z_o} \exp(-R/R_D) sech^2(z/z_o) \tag{1}$$

with $M_D = 5.6 \times 10^{10}\, M_\odot$, $R_D = 3.5\,\mathrm{kpc}$ and $z_o = 700\,\mathrm{pc}$.

The bulge and halo components are given by

$$\rho_B = \frac{M_B}{2\pi} \frac{a}{r(r+a)^3} \tag{2}$$

$$\rho_H = \frac{M_H \alpha}{2\pi^{3/2} r_{cut}} \frac{\exp(-r^2/r_{cut}^2)}{(r^2+\gamma^2)} \tag{3}$$

where $M_B = 1.87 \times 10^{10}\, M_\odot$, $a = 525\,\mathrm{pc}$, $M_H = 7.84 \times 10^{10}\, M_\odot$, $\gamma = 3.5\,\mathrm{kpc}$ and $r_{cut} = 84\,\mathrm{kpc}$. The model is represente by 216,808 particles, $N_D = 40\,960$, $N_B = 4\,096$ and $N_H = 171\,752$ with a softening of 175 pc for all the particles. In Figure 1 we show the rotation curve for this galaxy. We refer the reader to Hernquist (1993) for a detailed description of the technique on how to set up the galaxy model.

For the satellite we employed a self-consistent King profile (King 1966) which represents a good fit to early-type and nucleated dwarf galaxies (Vader & Chaboyer 1994). Three different models were considered in order to address the role of the internal structure of the satellite in the heating and thicknening of the stellar disk. These models are similar, in mass, to SMC and LMC of our Milky Way with masses of $5.6 \times 10^{10}\, M_\odot$ and $1.12 \times 10^{10}\, M_\odot$.

2.2. *Numerical technique and orbital parameters*

To evolve our simulations we use a treecode with a tolerance parameter $\theta_{tol} = 0.75$ and an integration timestep of 1.3 Myr. Quadrupole terms are included to compute forces between particles (Barnes & Hut 1986; Hernquist 1987).

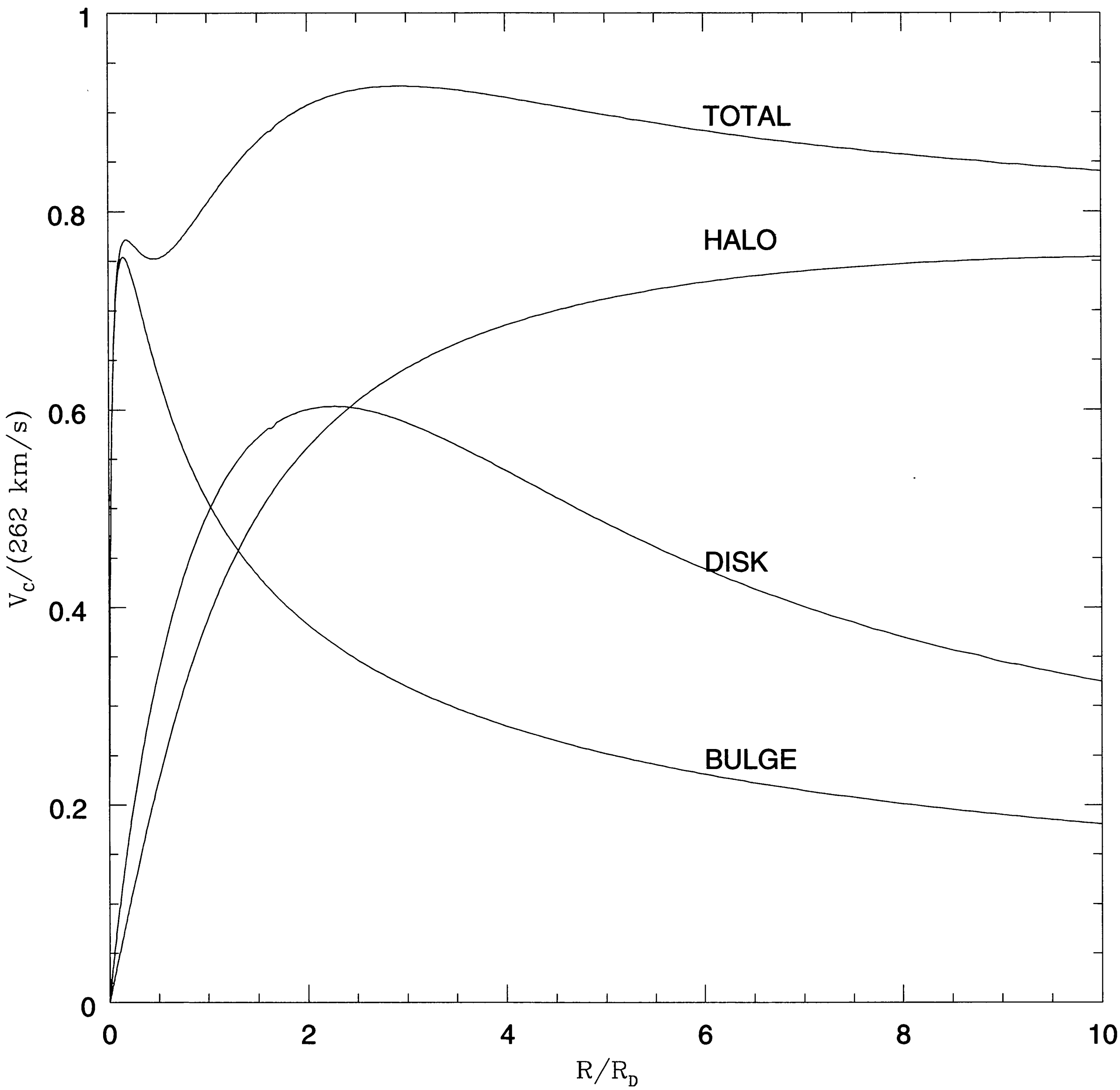

Fig. 1. The rotation curve for our disk galaxy model.

We have carried out total 16 simulations to explore a wide range of orbital parameters such as its inclination with respect to disk plane, eccentricities and different apocentric radii. We carried out a serie of 7 additional simulations with a less and a more massive bulge and by keeping the same disk and halo components with the aim of determining the role of the central part of the galaxy in the heating and thickening of the stellar disk. The masses for these new bulges were $1.12 \times 10^{10} M_{\odot}$ and $3.73 \times 10^{10} M_{\odot}$ repectively. The lower bulge mass limit was chosen to ensure disk stability against bar formation during the time the simulation takes. We did not intend a larger reduction of the bulge mass because it requires to increase the number of halo particles by at least a factor of 5 to keep stable the disk (e.g., WMH).

3. DISK RESPONSE TO THE INFALLING SATELLITE

As the satellite sinks to the galactic center it transfers energy and angular momentum to its surroundings (QHF, HC). Part of this orbital energy goes to the disk in random motions by increasing its scalelength and stability Q parameter. However, there is also a coherent response of the disk to the infalling satellite in the way of a tilting and warping. How the stellar disk responds is strongly correlated with the relative orientation of the disk and satellite angular momenta. In what follows we summarize our main findings.

3.1. *Thickening and Heating of the Disk*

In general, the stellar disk is more susceptible to damage by a satellite following a prograde orbit than by its retrograde counterpart. This result suggest a resonant coupling between satellite orbit and disk stars. In general, σ_R and σ_ϕ responds more strongly to the accretion event than σ_z indicating that Toomre's stability Q parameter is more sensitive than the vertical scalelength of the disk. Clearly, the final outcome depends on the mass and compactness of the satellite being accreted.

We found that models with a larger bulge/disk mass ratio reduce the damaging effects on the disk resulting from the accretion event suggesting that some resonances (e.g. Lindbland resonances) may play an important role. This allow us to undertand why WMH got a $\sim$ 60% thickening increase in their bulgeless galaxy simulation.

3.2. *Tilting and Warping of the Disk*

A general outcome of infalling satellites on retrograde orbits is to produce tilted and warped disks. In some cases, the disk is tilted by about $\sim 11^o$ with respect to its initial orientation of its angular momentum. However, and important fraction of the initial angular momentum of the satellite remains in its debris and another part goes to the halo of the galaxy. We were able to identify, despite being weak, warps. In the most favourable case this departure was less than 1.75 kpc from the disk plane corresponding to an angle $< 7^o$.

4. COMPARISON WITH TÓTH & OSTRIKER'S PREDICTION

One of our main results is that the limits on the accretion rate derived by Tóth & Ostriker (1992) are too strict. We found that they overestimate the damaging effects of satellite accretion by a factor of $2-3$ and in some cases is even larger.

We have good reasons to consider that our own results are a significant overestimate of the extent of the damage:

(i) The gaseous component, which we ignored, may play an important role in sustaining spiral structure in galaxies and hence, keeping lower values for the stability Q parameter.

(ii) Our satellites are already quite close to the disk and the galaxy model has a relatively low mass halo. It is likely that we underestimate disruptive effects on the satellite before it begins to interact strongly with the disk (see HC). However, a full treatment will require larger simulations and cosmological initial conditions.

There are several reasons that may explain the nonnegligible differences between TO's predictions and our results. Between the most important we can mention the following:

(1) They assume a local deposition of the orbital energy of the satellite in the disk. However, the formation of warps, spiral structure and tilting clearly indicates that such a suposition is untenable.

(2) They did not make any distinction between prograde and retrograde orbits.

(3) The responsiveness of the halo is ignored by obviuos limitations of their treatment.

(4) A satellite with internal degrees is not cosidered. This is important because the satellite has the capacity to absorb part of its own orbital energy which is carried away by the tidally disrupted material.

5. RIGID HALOES AND DISK RESPONSE

Finally, we address the importance of the responsiveness of the halo to the accretion of satellites. To this end, we replaced our live halo by a rigid one for our galaxy model. Dynamical friction was incorporated using Chandrasekhar's expression [2]:

$$\mathbf{F}_{df} = -\frac{4\pi \ln \Lambda G^2 M_S^2 \rho_H(r)}{v_S^3}[\, \mathrm{erf}(X) - \frac{2X}{\sqrt{\pi}}\, \mathrm{e}^{-X^2}]\, \mathbf{v}_S. \tag{4}$$

where $X = v_S/(2^{1/2}\sigma(r))$ and $\ln\Lambda$ is the Coulomb logarithm. M_S and ρ_H are the satellite mass and the *local* density of the halo at the satellite center; v_S and $\sigma(r)$ are the satellite velocity relative to the background and the local dispersion velocity of the halo at position r, respectively (Chandrasekhar 1960, Binney & Tremaine 1987).

In this case, the changes of the planar components of the velocity ellipsoid are similar to the ones obtained with a live halo. This suggest that limits on the accreted material based enterely on Toomre's Q parameter will be the same not matter how we represent the halo component. However, the vertical structure of the disk is strongly affected indicating a migthy coupling with the responsiveness of the halo resulting in larger increase of the vertical scalelength by a factor of$1.5-2$. The importance of the responsiveness of the halo becomes more obvious as we consider more massive satellites.

6. CONCLUSIONS

Our main conclusions are as follows:

TO's limits on the amount of material than a disk galaxy can accrete is too restrictive. They overestimate the damaging effects (heating and thickening) by a nonneglegible factor of $2-3$ at the Solar radius. Even, our results may be an overestimation due we have ignored cooling process involving the gas component. We found that a rigid potential for the halo component leads to larger thickening of the disk by a factor of $1.5-2$.

Prograde and retrograde orbits have a different effect in the disk structure. Prograde orbits tend to heating and thickening the disk while their retrograde counterparts tend to tilting and warping it. Thus, a massive satellite as large as $0.2\,M_D$ on a retrograde orbit can be accreted by the galaxy without producing a substantial damage to the disk.

It was difficult to identify large warp structures, may be this is due that our satellite orbits are elongated with periods that are asynchronous with the period of perturbed disk stars.

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