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Two characteristics of thick disks formed through minor mergers: Orbital eccentricities and stellar excess

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Abstract. In this contribution, we will present two results we have recently obtained in studying the impact of satellite(s) accretions on stellar disks, and that concern: (1) the distribution of the eccentricities of stars in thick disks; (2) the characteristics of the vertical surface density profiles of thick disks, and in particular the presence of a "stellar excess" at great heights ($z > 2$ kpc) from the galaxy mid-plane.

1. INTRODUCTION

Minor mergers are considered one of the main possible mechanisms responsible of the formation of thick stellar disks in galaxies, through the violent kinematical heating of a pre-existing thin stellar component, as a number of numerical studies have shown in the last twenty years ([1–7], among others). They can indeed reproduce:

- the range of scaleheights measured in the Milky Way (MW) thick disk ([8–12]) and in the external galaxies ([13–16]);
- the rotational lag of stars in the thick disk with respect to those in their thin counterparts ([17–20]);
- the presence (and fraction) of counter-rotating stars observed in some external galaxies (see [4, 20] and [7]);
- the observed correlations of the thick disk scale-heights with the galaxy mass ([16]) and the Hubble type ([21]);
- the different metal content and α-element abundances of thick and thin disk components (see, for ex, [22] this volume, and [5]).

Some of these properties can also be reproduced by other formation scenarios ([23–26]), thus complicating the detailed understanding of their origin. Since thick disks are observed in a variety of environments and all along the Hubble sequence of galaxy disks, it is also possible that several different processes, and not simply a single one, are responsible of their formation in different galaxies. Once formed, other mechanisms may have also have played a role in determining their evolution and characteristics (radial migration, for example, [27–29]), thus further complicating the situation.

While minor mergers can successfully reproduce a number of properties of the MW and extragalactic thick disks, they have difficulty in explaining:

- the presence of thick stellar components in late-type bulgeless galaxies ([16]). Satellite(s) accretion is usually accompanied by gas losing angular momentum and may lead to the formation or growth

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of a bulge. However, note this is currently a limitation of all the main mechanisms proposed for the formation of thick disks;

– the nearly constant thick disk scale height with distance from galaxy centers, that seems to characterize some extragalactic thick disks ([26, 30]). The two caveats here are that: (1) the thick disk scale height, as well as its dependence on the distance from the galaxy center, depend strongly on the gas fraction present in the galaxy disk before the merger. If thick disks formed by minor mergers at early epochs ($z{\sim}2$), we can reasonably assume that the pre-existing thin disks were gas rich ($f_{gas}{\sim}50-60\%$), which limits both the amount of local heating and the amplitude of the flaring ([6, 31]); (2) quantifying the thick disk scale heights in the outer disk regions requires the detection of extremely low surface brightness levels, and this is still very challenging (see discussions in [3] and [30]).

Recently, numerical models have started to characterize the signatures that different mechanisms imprint on thick disk components, in order to differentiate the (main) formation mechanism. In the next two sections we will discuss two results we have recently obtained in studying the impact of satellite(s) accretions on stellar disks, and that concern: (1) the distribution of the eccentricities of stars in thick disks (see [32]); (2) the characteristics of the vertical surface density profiles of thick disks, and in particular the presence of a "stellar excess" at great heights (z>2 kpc) from the galaxy mid-plane (see [6]).

2. STELLAR ECCENTRICITIES

Comparing simulations of the various mechanisms proposed for thick disk formation, [33] pointed out the distinctive differences between the eccentricity distributions predicted by each of them. The four scenarios they considered were: thick disk formation by radial migration ([27]); heating of a pre-existing thin disk by minor mergers ([3]); direct accretion of disrupted satellites ([24]); and formation by gas-rich mergers ([25]). The comparison of these four models led them to conclude that: (1) the accretion scenario predicts a broad distribution of stellar eccentricities, e, quite symmetric with respect to its peak at around $e = 0.5$; (2) the radial migration scenario produces a distribution quite narrow and symmetric around its peak at $e = 0.25$–0.3; (3) the heating of a pre-existing thin disk produces a distribution with a peak around $e = 0.25$, with a secondary peak and tail at high eccentricities composed mostly of stars originally in the satellite galaxy; and (4) gas-rich mergers produce a result quite similar to the previous scenario, except for the absence of the secondary peak.

A comparison of the eccentricity distributions predicted by these four models with that of stars populating the thick disk in the solar neighborhood has been successively done, leading, for example, [34] to propose gas-rich mergers at early epochs as the most probable mechanism for the formation of the Galactic thick disk (see also [35–38] for further comparisons).

We have recently reinvestigated the conclusions of [33] concerning the distribution of orbital eccentricities of stars in thick disk generated by the heating of a pre-existing thin stellar disk through a minor merger, using N-body/SPH numerical simulations of interactions that span a range of gas fractions in the primary disk and initial orbital configurations. Our analysis ([32]) shows that the resulting eccentricity distributions have an approximately triangular shape, with a peak at 0.2–0.35, and a relatively smooth decline towards higher values. Stars originally in the satellite galaxy tend to have higher eccentricities (on average from $e = 0.45$ to $e = 0.75$), which is in general agreement with the models of [33], although in detail we find fewer stars with extreme values and no evidence of their secondary peak around $e = 0.8$. The absence of this high-eccentricity feature results in a distribution that qualitatively matches the observations (see Fig. 3 in [32]). Moreover, the increase in the orbital eccentricities of stars in the solar neighborhood with vertical distance from the Galactic mid-plane found by [34] can be qualitatively reproduced by our models, but only if the satellite is accreted onto a direct orbit (see Fig. 1). On the basis of these results, we thus speculate that if minor mergers were the dominant

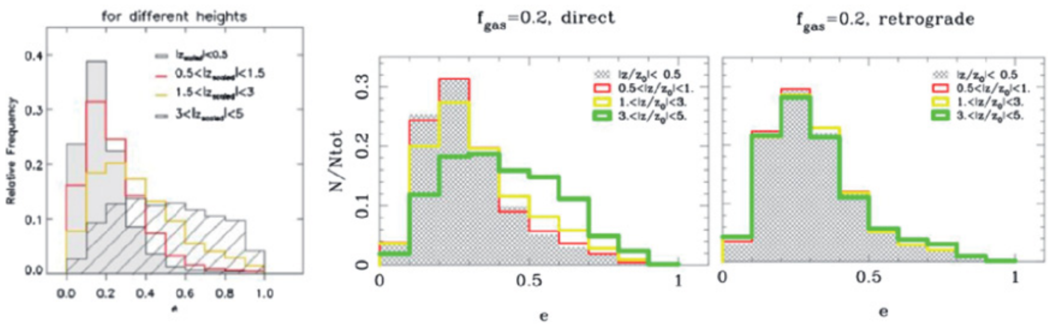

Figure 1. Height-dependence of the stellar eccentricity distribution of thick disk stars in the solar neighborhood (left panel: from [34], Fig. 2) and in N-body simulations of a direct and a retrograde 1:10 merger, with $f_{gas} = 20\%$ (respectively central and right panels: from [32], Fig. 4).

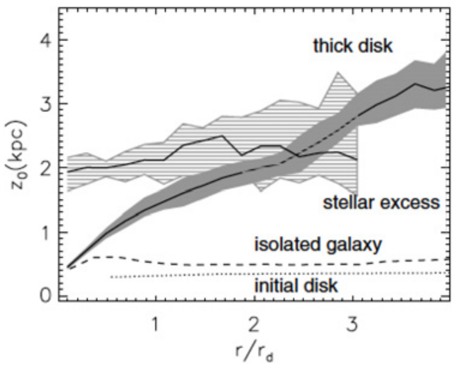

Figure 2. The scale heights z_0 of the merger-induced thick disk and stellar excess as function of radius in units of disk scale length, r/r_d, for dissipationless minor mergers with six sets of different initial orbital parameters. The shaded regions indicate the scatter in the scale heights. Most of this scatter results from the differences in initial orbital configurations. Also shown are the scale heights of the original stellar disk (dotted line) and after its evolution in isolation for 3 Gyr (dashed line). From [6], Fig. 4.

means of forming the Milky Way thick disk, the primary mechanism should be merging with satellite(s) on direct orbits.

3. STELLAR EXCESS AT GREAT DISTANCES FROM THE GALAXY MID-PLANE

It has recently been shown by [39] and [40] that minor mergers cannot only efficiently heat a pre-existing stellar disk, and thus forming a thick component, but also contribute to the building of galaxy halos, by ejecting thin disk (or bulge) stars at great vertical distances from the plane. We have recently investigated and characterized this "excess" of stars at great mid-plane heights (z>2 kpc), which is a naturally consequence of minor mergers, as a function of primary galaxy gas fraction and including consecutive minor mergers. Our results show that ([6]):

- the excess has morphological and kinematic properties which are distinct generally from those of thick disk stars;
- while the thick disk scale height increases with radius, the scale height of the stellar excess is constant with radius (see Fig. 2);

– the scale height of the thick disk decreases with an increase in the gas-to-stellar mass fraction of the primary disk, while that of the stellar excess does not: no significant dependence on the gas fraction in the primary disk is found, at least for $f_{gas} \leq 0.2$;
– stars in the stellar excess rotate slower than stars in the thick disk, and their kinematics are compatible with those of high-α abundant stars found recently by [41] in the solar neighborhood (see Fig. 11 in [6]);
– thick disks formed through instabilities in gas-rich disks at high redshift ([26]) do not result in any stellar excess at large disk scale heights, unlike the merger simulations.

An example of a disk galaxy showing an unusual vertical stellar distribution, characterized by the presence of a stellar excess (also called "extended component"), is NGC 4013, as recently shown by [42]. The main characteristics of the stellar excess observed in this galaxy, in particular the constancy of its scale height as a function of the distance from the galaxy center, are compatible with a minor merger origin, as our models show.

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