Orbital Eccentricity as a probe of Thick Disk Formation Scenarios

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ABSTRACT

We study the orbital properties of stars in four (published) simulations of thick disks formed by: i) accretion from disrupted satellites, ii) heating of a pre-existing thin disk by a minor merger, iii) radial migration and iv) gas rich mergers. We find that the distribution of orbital eccentricities are predicted to be different for each model: a prominent peak at low eccentricity is expected for the heating, migration and gas-rich merging scenarios, while the eccentricity distribution is broader and shifted towards higher values for the accretion model. These differences can be traced back to whether the bulk of the stars in each case is formed in-situ or is accreted, and are robust to the peculiarities of each model. A simple test based on the eccentricity distribution of nearby thick disk stars may thus help elucidate the dominant formation mechanism of the Galactic thick disk.

1 INTRODUCTION

Several mechanisms have been proposed to explain the formation of thick disks in galaxies (see Majewski 1993). However it is still unclear by which of these mechanisms thick disks preferentially form. This is despite the fact that more than 25 years have passed since it was first detected in the Milky Way (Gilmore & Reid 1983), and that it has been established that this component appears to be ubiquitous in late-type systems (e.g. Yoachim & Dalcanton 2008, and references therein).

Amongst the scenarios proposed to explain the formation of the thick disks are the direct accretion of stars from disrupted satellites (e.g. Abadi et al. 2003b), the thickening of a pre-existing thin disk through a minor merger (e.g. Quinn et al. 1993; Villalobos & Helmi 2008; Kazantzidis et al. 2008), the scattering or migration of stars by spiral arms (e.g. Schönrich & Binney 2009a; Roshkar et al. 2008; Schönrich & Binney 2009b), and in-situ triggered star formation during/after gas-rich mergers (e.g. Brook et al. 2005; Bournaud et al. 2007).

Even though studies of external galaxies have been fundamental to establish the statistical properties of thick disks, it is likely that only for the Galactic thick disk we will be able to unravel its evolutionary path. For example, measurements of the phase-space coordinates for nearby thick disk stars allows reconstruction of their orbits, which contain imprints of the dynamical history, while their chemical abundances encode information about their sites of origin. Time is ripe to delve into more detailed predictions for the above-mentioned scenarios, because these have reached a level of maturity and detail that they warrant and permit a nearly direct comparison to observations.

In this Letter we investigate how the orbits of thick disk stars can be used to distinguish between the various formation channels. In particular, we focus on the predicted eccentricity distributions. We expect our findings to be applied soon to samples of nearby thick disk stars from SEGUE (Yanny et al. 2009; Smith et al. 2009) and RAVE (Steinmetz et al. 2006, Breddels et al. submitted), and in the long term, to the Gaia dataset which will provide much more accurate information for much larger samples of stars spanning a wide range of distances from the Sun. The orbital eccentricity-test should help to elucidate the dominant mechanism by which the Galactic thick disk formed.

2 NUMERICAL EXPERIMENTS

We have gathered four existing numerical simulations of late-type galaxies that, having all developed a thick disk component, clearly differ in the dominant formation mechanism. These are:

(i) accretion and disruption of satellites (Abadi et al. 2003b),
(ii) disk heating by a minor merger (Villalobos & Helmi 2008),
(iii) radial migration via resonant scattering (Roškar et al. 2008),
(iv) in-situ formation during/after a gas-rich merger (Brook et al. 2004, 2005).

2.1 Thick disk formation models

Because each of the simulations mentioned above have been already introduced in the literature, here we will only review their
Table 1. Relevant parameters for each of the simulations. (1) model, (2) Virial mass, (3) Bulge/Spheroid mass (4) Disk mass (thin+thick), (5) Thin disk scale-height (from a double power law fit to the vertical mass profile), (6) Thick disk scale-height, (7) Radial scale length of the thin disk, (8) softening lengths, (9) reference to the original articles. For comparison, estimated values for the Milky Way have also been included. For the cosmological simulations, the virial masses are defined as the mass enclosed within the radius where the local density falls below $\Delta = 100$ times the critical density of the universe. A Hubble constant $H_0 = 70 \text{Mpc}^{-1}\text{km/s}$ is assumed when necessary. Disks scale-heights have been determined by fitting double-exponential laws to the vertical stellar density profile in the cylindrical shell $2 < R/R_d < 3$.

| Scenario     | $M_{\text{vir}}$ [$10^{10}M_\odot$] | $M_{\text{bulge}}$ [$10^{10}M_\odot$] | $M_{\text{disk}}$ [$10^{10}M_\odot$] | $z_0$ (thin) [kpc] | $z_0$ (thick) [kpc] | $R_d$ [kpc] | $\epsilon$ [kpc] | Reference       |
|--------------|-----------------------------------|-------------------------------------|---------------------------------|---------------------|---------------------|-----------|---------------|----------------|
| accretion    | 87                                | 6.7                                 | 2.8                             | 0.5                 | 2.3                 | 4.1       | 0.50          | Abadi et al. (2003a,b) |
| heating      | 50                                | –                                   | 1.2                             | –                   | 1.2                 | –         | 0.01          | Villalobos & Helmi (2008) |
| migration    | 100                               | 4.8                                 | 3.0                             | 0.3                 | 0.9                 | 3.5       | 0.05          | Roskar et al. (2008)     |
| merger       | 71                                | 2.1                                 | 3.4                             | 0.3                 | 1.0                 | 2.9       | 0.40          | Brook et al. (2004)      |
| Milky Way    | 60-200                            | 1.0                                 | 7-10                            | 0.3                 | 0.9                 | 3.5       | –             | Turon et al. (2008)      |

main relevant features, referring the reader to the original papers for further details. Table 1 summarizes their key parameters.

2.1.1 Accretion scenario

Abadi et al. (2003) showed that within the ΛCDM paradigm, the accretion of stars from disrupting satellites in approximately co-planar orbits may give rise to an old thick disk component that comprises about one-third of the mass of the much younger thin disk.

In our sample we include the galaxy presented in Abadi et al. (2003), which formed in a cosmological N-body/SPH simulation. This object, with a virial mass of the order of that of the Milky Way, was selected from a low-resolution simulation of a large volume of the Universe; and later re-simulated with much higher resolution. In this high resolution run, the mass per baryonic particle is $\sim 3 \times 10^5 M_\odot$. The final mass for the thick disk in this galaxy (derived via a dynamical decomposition) is $1.1 \times 10^{10} M_\odot$.

2.1.2 Heating scenario

In this model, a thick disk is formed by the dynamical heating that is induced by a massive satellite merging with a primordial, rotationally supported thin disk. This scenario has been explored recently by e.g. Villalobos & Helmi (2008); Kazantzidis et al. (2008), who have shown that 5:1 mergers and with a wide range of orbital inclinations generate thick disks whose properties are in reasonable agreement with observations. In such a model, the bulk of stars that end up in the thick disk originate from the primordial disk rather than from the accreted satellite (Villalobos & Helmi 2008).

In our analysis we include one of the numerical experiments presented in Villalobos & Helmi (2008). In these simulations, the mass ratio between the satellite and the host is 0.2 and its initial orbit is prograde and inclined by 30° with respect to the host disk. The mass per stellar particle in the simulation is $m_p = 1.2 \times 10^4 M_\odot$, and the thick disk has a final mass of $1.2 \times 10^9 M_\odot$. It is important to clarify that only a small fraction of the thin disk component is present at the end of the simulation ($\sim 15 - 20\%$ of the mass of the original disk). This implies that, for this remnant to be the thick disk of a late-type galaxy, a new thin disk should form later from the cooling of fresh gas. This will lead to structural changes in the thicker component, which are not considered here. Nevertheless, if the growth of the new disk is adiabatic, then many characteristics, and in particular the eccentricities, are not expected to be dramatically different (Villalobos 2009).

2.1.3 Radial Migration scenario

Stars in the thin disk may be trapped onto resonant corotation with spiral arms, and may migrate inwards and outwards along the spiral waves approximately conserving their angular momenta (and hence eccentricity) and without leading to significant heating in the disk (Sellwood & Binney 2002). However, since the vertical velocity dispersion of stellar disks correlates with their surface brightness (Kereš et al. 2005), the radial migration of stars from the inner regions (kinematically hotter) will result in the formation of a thicker disk component.

Although this process has not been formally proposed as a thick disk formation scenario, numerical simulations suggest that a modest thick component may be built. Therefore, we include in our sample the simulation presented in Roskar et al. (2008) run with the goal of characterizing the migration that takes place in galactic disks. The simulation starts with a dark matter halo of $\sim 10^{12} M_\odot$ where 10% of this mass is in the form of a hot halo gas component. This gas is allowed to cool and form stars self-consistently, mimicking the quiescent growth of disk galaxies, over a period of 10 Gyr. The initial mass resolution is $10^6 M_\odot$ for the baryons, and stellar particles have on average masses $3 \times 10^4 M_\odot$.

2.1.4 Gas-rich merger scenario

The last scenario we explore consists in the formation of a thick rotating component during an active epoch of gas rich mergers in the past history of a galaxy (Brook et al. 2004, 2005). This formation channel differs fundamentally from the accretion model because the bulk of thick disk stars are born in-situ rather than being accreted from satellites. In this sense, this scenario might show certain similarities with the heating model. However, the latter requires the existence of a thin disk at early times, $z > 1$, in contrast to the merger scenario where the stars are already born in a hotter component.

Here we analyze the simulated galaxy introduced in Brook et al. (2004). It formed in a semi-cosmological N-body/SPH simulation that includes heating/cooling of gas, star formation, feedback and chemical enrichment. Its dark halo has a quiescent merger history after $z \sim 2$, and a final baryonic content of the galaxy is $\sim 5 \times 10^{11} M_\odot$ (see Table 1). The mass per baryonic particle is $\sim 2 \times 10^9 M_\odot$. The mass of the thick disk in this galaxy is $\sim 2.2 \times 10^9 M_\odot$, identified as old stars ($8.5 < \text{age} < 10.5$) with relatively high rotation velocity ($V_{\text{rot}} > 50 \text{km/s}$).
The scenarios described in this Section are capable of producing a rotationally supported hot component whose properties resemble the ‘thick disks’ in galaxies. However, the relative preponderance of such thick components does vary from galaxy to galaxy in our simulations. This is illustrated in Figure 1, where we show with solid dots the vertical mass profiles for each case in a cylindrical shell $2 < R/R_d < 3$; which minimizes the contribution from bars and bulges. Additionally, in the accretion model, particles identified as “spheroid” in Abadi et al. (2003b) have been removed (see Section 3). The error bars correspond to the rms obtained from one hundred bootstrap re-samples of the data, and they are generally smaller than the dot’s sizes. The black solid lines show the best-fit double exponential profile found for each galaxy, together with its decomposition into the “thin” and the “thick” disk contributions, in red dotted lines. This decomposition is generally robust, although correlations exist between the relative density of each component and the scale-height of the thick disk. The scale-heights $z_0$ obtained by minimizing $\chi^2$ are quoted in each panel, and the typical errors are of order $5 - 10\%$ for $z_0^{\text{thin}}$ and $\sim 20 - 30\%$ for the thick component. For the migration scenario, the uncertainties are larger due to the stronger dominance of the thin disk, and are $15\%$ and $60\%$ for $z_0^{\text{thin}}$ and $z_0$, respectively. Nevertheless, in all cases, the results presented below are robust to changes in the value of $z_0$ within the uncertainties.

Differences in the relevance of the thick component depend not only on the net efficiency of the respective formation process, but may also be influenced by the different initial conditions and simulation techniques (e.g. only the accretion and merger scenarios actually account for the full cosmological framework). Because of these basic differences between simulations, global properties such as the mass, rotation and size of each formed thick disk are expected to be diverse. Our focus, however, is on contrasting the specific dynamical properties of the stars in the thick component for each case, and in particular, their orbital eccentricities, which as we shall see below, are fundamentally related to the physical mechanism by which this component was built.

In order to facilitate comparisons between the thick disks in our galaxies and in particular, also to that of the Milky Way, we re-scale the radial and vertical distances of the stellar particles in each galaxy by their corresponding thin disk scale-lengths and thick disk scale-heights. In what follows, we will focus our attention on “solar neighbourhood volumes”, equivalent to cylindrical shells between two and three scale-radii of the thin disk ($2 < R/R_d < 3$). For comparison, $R_G/R_d \sim 2.2 - 2.4$, assuming a scale radius of $R_d = 3.5$ kpc for the Milky Way.

### 2.2 Modelling of the orbits

Kinematical surveys such as RAVE, SEGUE and ultimately Gaia provide phase-space coordinates of stars around the position of the Sun. This instantaneous information may be used to recover their plausible past orbits. This requires modelling the (unknown) Galactic potential, and possibly its evolution, which implies that the orbital parameters derived for each star generally suffer from a certain degree of uncertainty, even if measurement errors are neglected.

On the other hand, our numerical simulations allow us to track in time each particle, with full orbits that are known. Nevertheless, we prefer to mimic observations, and therefore we use the present-day position and velocity of each stellar particle as initial conditions for the integration of their orbits in the best-fit potential of their host galaxy. We model each galaxy as a four component system with an NFW (Navarro et al. 1997) dark halo, a Hernquist profile (Hernquist 1990) for the bulge and two Miyamoto-Nagai disks (Miyamoto & Nagai 1975) corresponding to the thin and thick disks contributions. The mass associated with each of these components is known for each simulation (see Table 1), and their various scale-lengths are chosen by requiring a good match to the circular velocity profile of the system up to a distance of 20 kpc. This is along the lines of previous work, where the circular velocity of the Milky Way is often used to constrain the model parameters (e.g. Helmi et al. 2006).

We define eccentricity as $e = (r_{ap} - r_{pe})/(r_{ap} + r_{pe})$, where $r_{ap}$ and $r_{pe}$ correspond, respectively, to the apo- and pericenter distance of the last orbit of each particle. With this definition, for a circular velocity curve modeled with $\sim 10\%$ accuracy, the eccentricities obtained by numerical integration show a scatter $\pm 0.1 - 0.2$ around their true value with no systematic trends (see Fig. 3). Larger deviations are found as the eccentricity increases.

### 3 RESULTS

Baryons in galaxies are generally sorted in several components: a bulge, a disk (thin+thick) and a more extended and diffuse

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1 For the simulation by Villalobos & Helmi (2008) we assume the scale-length to be that of the Milky Way thin disk: $R_G = 3.5$ kpc, although our conclusions do not fundamentally depend on this choice.

2 For the migration and merger scenarios only the total (thin + thick) mass of the disk is known. For these cases the relative mass ratio between the thin and thick components is also a free parameter.
The lowermost bin $|z/z_0| < 0.5$ is largely dominated by thin disk stars with circular motions, as can be seen by the strong peak around $\epsilon \sim 0.15$ in the top left panel of Figure 2. These stellar particles formed in-situ through local conversion of gas settled in a disk, into stars (blue empty histogram) within the main galaxy. As we move away from the plane the thick disk gains importance and the eccentricity distributions become flatter as the fraction of accreted stars increases. Further above and below the plane, the distribution is dominated by particles from the spheroidal component, with even higher characteristic eccentricities, i.e. $\epsilon \sim 0.7$. These changes in the relative preponderance of the thin, thick and spheroidal components can be seen as their fractional contribution (magenta dot-dashed, green long-dashed and black solid, respectively) to each eccentricity on the bottom panel of all $|z|$-bins. Here, we have used the dynamical decomposition performed in Abadi et al. (2003b) to assign stars to a given component.

This galaxy, introduced in Abadi et al. (2003a,b), has a large stellar spheroid that contains more than $\sim 70\%$ of the total luminous mass. Figure 2 shows that its contribution dominates the high eccentricity bins at all heights above/below the plane. To highlight the properties of the thick disk, and also to avoid confusion on the interpretation of our results and its comparison with other simulated galaxies (lacking such a prominent spheroidal component), we will exclude in what follows any stellar particle that have been assigned to the spheroid by the analysis performed in Abadi et al. (2003b).

Figure 3 shows that the eccentricity distributions vary according to the different formation channels of the thick disk. Each panel corresponds to one particular model: accretion (top left), heating (top right), migration (bottom left) and merger (bottom right). When relevant, the contributions from stars formed “in-situ” or “accreted” have been highlighted. In order to minimize the contribution from thin disk stars, we have focused on the vertical bin $1 < |z/z_0| < 3$. On the other hand, to avoid contamination from the spheroids in our simulations (this is unlikely to be important for the Galactic stellar halo because of its very low density), we only consider stars with rotational velocity $v_\phi > 50$ km s$^{-1}$. This corresponds to average azimuthal velocity at which there is a clear excess of stars with velocities larger than this threshold compared to the distribution at $v_\phi < -50$ km s$^{-1}$ in our simulations. Under the assumption of a non-rotating spheroidal component, this criterion will minimize the contribution of the stellar halo in our samples. Nonetheless, we have checked that our results are not strongly sensitive to this assumption. The $v_\phi > 50$ km s$^{-1}$ cut removes 33 per cent of the stars in Brook’s model, but has a negligible effect in the simulation by Villalobos & Helmi and Roškar et al. due to the suppressed contribution of satellite accretion. Recall that for the Abadi’s galaxy we have removed all the spheroid identified by the dynamical decomposition. Cuts on the cylindrical radii ($2 < R/R_d < 3$) also help to elude the contributions from central bars and bulges.

Figure 3 shows that the eccentricity distributions of stellar particles in these “solar neighbourhood” regions, and between one and three thick disk scale-heights above/below the plane, are different according to each model. For the accretion scenario, the distribution is very broad, with a median eccentricity $(\epsilon) \sim 0.5$ (in good agreement with the accreted component in Read et al. 2008). On the other hand, the heating of a pre-existing thin disk by a minor merger gives rise to a bimodal distribution. The dominant peak is at low eccentricity $\epsilon \sim 0.2 - 0.3$ and associated to the stars from the progenitor disk, while the second peak at $\epsilon \sim 0.8$, is brought by the disrupted satellite. Radial migration tends to preserve the initial (low) eccentricity distribution, with only one peak present at $(\epsilon) \sim 0.2$ and with a sharp cut-off at $\epsilon \sim 0.6$. Finally, in the merger scenario a prominent peak around $\epsilon \sim 0.2$ is visible which is associated to stars formed in-situ during the epoch of active gas-rich mergers. But like for the accretion scenario, accreted stars from infalling satellites contribute to a high-eccentricity tail.

Interestingly, Figure 3 shows, as expected, that stars formed in-situ have low eccentricity orbits regardless the mechanism (heat-
4 CONCLUSIONS

In this Letter we have analyzed four numerical simulations of galaxies hosting a thick disk component of fundamentally different origin: (i) accretion of satellites, (ii) heating of a pre-existing disk by a 5:1 mass-ratio merger, (iii) radial migration by resonant scattering and (iv) gas-rich mergers at high-redshift.

We have compared the eccentricity distributions predicted by these different models for stellar particles in the “solar neighbourhood”, i.e. located in a cylindrical shell of radius $2 < R/R_d < 3$ and with heights $1 < |z/z_d| < 3$. Thick disk stars formed in-situ have low orbital eccentricities $\epsilon \sim 0.2 - 0.3$, independently of the mechanism that brought them high above/below the plane: gas-rich mergers, heating or migration. On the other hand, and again regardless of the particular model, accreted stars always dominate the high-eccentricity tail of the distributions. Therefore, the characterization of the eccentricity distribution of the thick disk can be used to establish if this component was formed by the accretion of satellites (Abadi et al. 2003) or alternatively locally within the main galaxy [Brook et al. 2008, Villalobos & Helmi 2008, Koskarel 2008]. However, given the various limitations of our set of simulations, we cannot claim that it will be possible to make an unequivocal classification among models (i) -- (iv) based only on eccentricity.

Nevertheless, the differences between the orbital eccentricities of in-situ and accreted stellar particles are encouraging in view of the various kinematic surveys mapping our Galaxy today and in the near future. We believe that with a reasonable guess of the Milky Way potential, the analysis of the eccentricity distribution of thick disk stars at approximately 1-3 scale-heights should shed light on the formation path of the Galactic thick disk.

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