THE MYSTERY OF THE σ -BUMP—A NEW SIGNATURE FOR MAJOR MERGERS IN EARLY-TYPE GALAXIES?

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ABSTRACT

The stellar velocity dispersion as a function of the galactocentric radius of an early-type galaxy can generally be well approximated by a power law $\sigma \propto r^{\beta}$. However, some observed dispersion profiles show a deviation from this fit at intermediate radii, usually between one and three R_{eff} , where the velocity dispersion remains constant with radius, showing a bump-like behavior, which we term the " σ "-bump. To understand the origin of this σ -bump, we study a set of simulated early-type galaxies formed in major mergers. We find the σ -bump in all of our simulated early-type galaxies, with the size and position of the bump slightly varying from galaxy to galaxy, suggesting that the bump is a characteristic of the major merger formation scenario. The feature can be seen both in the intrinsic and projected stellar velocity dispersions. In contrast to shells that form during the merger event but evolve with time and finally disappear, the σ -bump is not seen in the dark matter and gas components and we therefore conclude that it is a purely stellar feature of merger remnants.

Key words: galaxies: elliptical and lenticular, cD - galaxies: kinematics and dynamics - methods: numerical

Online-only material: color figures

1. INTRODUCTION

The kinematics of early-type galaxies (ETGs) has been a subject of interest for many years. Unfortunately, the stellar light decreases rapidly after one to two effective radii, allowing observations to reliably detect only the inner few effective radii (Proctor et al. 2009; Foster et al. 2013; Arnold et al. 2013). Thus, the outer halos cannot be studied by observing the stellar light directly.

However, there are several reasons why the outer regions are of interest, especially as this is where the dark matter becomes dominant and its properties can be tested. Romanowsky et al. (2003) for example found a steep Keplerian decline in the velocity dispersion of NGC 3379, resulting in discussions about the existence of a canonical dark halo (Dekel et al. 2005; Douglas et al. 2007). In addition, the kinematics of the stellar component in the regions far away from the center are most likely to preserve some indications of the formation history of the galaxy. For example, in S0 galaxies, the distinction between random motion and the ordered motion of a kinematically cold stellar disk component can reveal if the galaxy is actually a fading spiral galaxy or was formed from a minor merger, as discussed by Noordermeer et al. (2008) and Cortesi et al. (2013).

In order to study ETGs to larger radii, tracers are needed. These tracers need to emit enough light to be detectable as single objects even at large distances. Currently the most important tracers are planetary nebulae (PNe) and globular clusters (GCs). Planetary nebulae emit a large amount of their light in the [O III] λ 5007 line and can therefore be observed out to many effective radii, as seen in the famous example of NGC 5128 where PNe have been found out to 20 kpc by Hui et al. (1995) and out to 80 kpc by Peng et al. (2004). With spectrographs it is now possible to obtain not only the positions but also the line-of-sight velocities of hundreds of objects at large distances from the center (e.g., Méndez et al. 2009: 591 PNe in NGC 4697, Coccato et al. 2009: 450 PNe in NGC 4374).

Another possible tracer for the stellar dynamics in the outskirts of ETGs is GCs. Two groups of GCs can be distinguished: red, metal-rich GCs and blue, metal-poor GCs. Studies by Schuberth et al. (2010) and others provided evidence that the stellar field population is traced by red GCs, whereas blue GCs may have been accreted later. A total of more than 2500 GCs was recently studied by Pota et al. (2013) in 12 nearby ETGs.

In numerical simulations, one is not restricted by the decreasing surface brightness, but by resolution effects. However, with improved numerical techniques, the analysis of small-scale details of ETGs is now possible. For example, the shell structure of ETGs, first observed in NGC 1316 by Malin (1977), could be understood as due to disruption of an accreted galaxy (e.g., Toomre 1978; Schweizer 1986; Hernquist & Quinn 1988; Binney & Tremaine 2008; Cooper et al. 2011). Therefore, these shell structures can reveal information about the merger history of the galaxy.

To have a further indicator for the formation history of ETGs, we study in this Letter the velocity dispersions of merger remnants. The goal is to find residual kinematic signatures of the progenitor galaxies that are still detectable despite the violent relaxation experienced by the merging galaxies.

2. SIMULATIONS

We study 10 ETGs formed in isolated major mergers of both spiral–spiral and spiral–elliptical galaxies. For the simulations, we use the parallel TreeSPH-code Gadget-2 (Springel 2005), in which energy and entropy are manifestly conserved, including radiative cooling of a primordial hydrogen–helium composition. Star formation and supernova feedback are included, using the self-regulated model of Springel & Hernquist (2003). The description of the interstellar medium is based on a two-component model, where cool clouds are embedded in a surrounding medium of hot gas (McKee & Ostriker 1977; Johansson & Efstathiou 2006).

 Table 1

 Binary Merger Simulation Sample at a Time Step of 3 Gyr

Model	Ratio ^a	Orbit ^b	$f_{\rm gas}{}^{\rm c}$	Bulge ^d	BH ^e	$v_{\rm vir}{}^{\rm f}$	$R_{\rm eff}{}^{\rm g}$	β^{h}
11 NB NG 13	1:1	G13	0.0	No	Yes	160	8.48	-0.17
11 NB OBH 13	1:1	G13	0.2	No	Yes	160	6.15	-0.19
11 NG 13	1:1	G13	0.0	Yes	Yes	160	6.76	-0.17
11 OBH 09	1:1	G09	0.2	Yes	Yes	160	5.02	-0.22
11 OBH 13	1:1	G13	0.2	Yes	Yes	160	5.20	-0.20
31 ASF 01	3:1	G01	0.2	Yes	No	160	4.59	-0.21
31 O8BH 13	3:1	G13	0.8	Yes	Yes	160	2.56	-0.19
31 OBH 09 320	3:1	G09	0.2	Yes	Yes	320	10.42	-0.10
31 OBH 13	3:1	G13	0.2	Yes	Yes	160	5.22	-0.18
mix 11 OBH 13	1:1	G13	0.2	Yes	Yes	160	6.32	-0.18

Notes.

^a Initial mass ratio of the two galaxies.

^b Orbit type according to Naab & Burkert (2003), Naab et al. (2006), and Khochfar & Burkert (2006).

^c Initial gas fraction of the disks of the progenitor galaxies.

^d Do the progenitor galaxies contain a bulge?

^e Do the progenitor galaxies contain black holes?

^f Initial virial velocity in km s⁻¹.

^g Effective radius in kpc at 3 Gyr.

^h Slope for fitting $\sigma \propto r^{\beta}$ to the stellar component of the velocity dispersion at 3 Gyr in the range of 0–50 kpc.

Nine out of our 10 galaxies include a black hole (BH). To model its feedback, we use the model of Springel et al. (2005). To guarantee efficient merging in the simulations, BHs merge instantaneously as soon as one BH is within the other BH's smoothing length and its velocity has become smaller than the local sound speed of the surrounding particles. The progenitor disk galaxies are embedded in Hernquist-like dark matter halos with concentration parameters $c_s = 9$ of the corresponding Navarro–Frenk–White halo (Navarro et al. 1997). The two galaxies are separated by a pericenter distance $r_{peri} = r_{d,1} + r_{d,2}$ with a baryonic disk-scale radius $r_{d,1} = 3.5$ kpc for the primary galaxy and $r_{d,2} = 2.4$ kpc for the secondary galaxy in the case of a 3:1 merger. For more details about the simulations, see Johansson et al. (2009a), Johansson et al. (2009b), and Remus et al. (2013).

Our sample consists of five spiral–spiral mergers with a mass ratio of 1:1 for the progenitors and four mergers with a ratio of 3:1, as well as one mixed merger (spiral and elliptical formed by a 3:1 spiral–spiral merger). The merger parameters are described in detail in Table 1. To demonstrate our analysis, we use the 1:1 spiral–spiral merger 11 OBH 13, which has the following initial setup: inclinations $i_1 = -109^\circ$ and $i_2 = 180^\circ$, pericenter arguments $\omega_1 = 60^\circ$ and $\omega_2 = 0^\circ$, $v_{vir} = 160 \text{ km s}^{-1}$.

3. RESULTS

Observations have shown that the projected velocity dispersion (= root mean squared velocity) of the stellar component can in general be well-fitted by a power law (Douglas et al. 2007; Napolitano et al. 2009):

$$\sigma \propto r^{\beta}.$$
 (1)

We calculate the intrinsic velocity dispersion profiles for our spheroidals and fit a power law to the stellar component. Therefore, each directional component of the velocity dispersion is computed in radial bins as

$$\sigma_i(r) = \sqrt{\frac{\sum v_i(r)^2}{N} - \left(\frac{\sum v_i(r)}{N}\right)^2},$$
 (2)



Figure 1. Upper panel: stellar (black) and dark matter (blue) intrinsic velocity dispersion as a function of radius for galaxy 11 OBH 13. For the stellar component, the power-law fit is included (black dashed curve). The σ -bump (red arrow) as a positive deviation from a power-law behavior appears only in the stellar component. Lower panel: radial (green), tangential (blue), and azimuthal (orange) components of the stellar velocity dispersion. (A color version of this figure is available in the online journal.)

where the sum runs over all particles within the bin (the second summation equals zero in stationary systems and we include it here for the sake of the early time steps). The intrinsic velocity dispersion is then calculated as

$$\sigma = \sqrt{\sigma_1^2 + \sigma_2^2 + \sigma_3^2}.$$
 (3)

The upper panel of Figure 1 shows the velocity dispersion of the stellar and dark matter components of our example galaxy, 11 OBH 13, as a function of radius, together with a power-law fit



Figure 2. σ -bump in our 10 simulated galaxies. Left column: 1:1 mergers, right column: 3:1 mergers (all at 3 Gyr). Upper panels: velocity dispersion of the different spheroids (solid lines) and their corresponding power laws (dashed lines) as a function of effective radius. For better readability, we shift the dispersion profiles for all mergers except 11 NB OBH 13, 31 ASF 01, and 31 O8BH 09 320 by multiples of 50 km s⁻¹. The lower panel displays the difference between the velocity dispersion and its best fit power law.

(A color version of this figure is available in the online journal.)

to the stellar component. For our sample of spheroidals, we find the mean of the power-law exponent to be $\beta = -0.18 \pm 0.04$ for the stellar component (see Table 1). This may be compared with the stellar slopes of Dekel et al. (2005) ($\beta = -0.4 \pm 0.1$ in projection), hydrodynamical cosmological zoom-in simulations ($\beta = -0.05 \pm 0.06$), and large-scale hydrodynamical cosmological simulations ($\beta = -0.003 \pm 0.135$) of Remus et al. (2013).

We include more than 680,000 (450,000) stellar particles in each 1:1 (3:1) ETG, with each bin having a bin width of 0.1 kpc and containing more than 1000 particles for radii up to 20 kpc. To ensure that our results do not depend on the binning, we tested equal-mass bins (1500 particles per bin) and other equal-radius bin widths, but found no differences.

As can be seen in Figure 1, the stellar velocity dispersion generally follows a power law, but shows some deviations. The innermost deviation of the velocity dispersion from a power law within 2 kpc is due to very bound progenitor bulge stars in the deep gravitational potential at the centers of the galaxies. Other deviations from the power law are caused by shell structures. Shells can form in major mergers, e.g., described by Cooper et al. (2011), leading to an ejection of stars in density waves (Schweizer 1986). Therefore, the velocity dispersion varies at the radii 30–50 kpc where shells are present.

We distinguish between the deviation in the range of 5–15 kpc and the oscillations at larger radii. The latter are clearly linked to regions of high particle density, visually identified as shell structures. In the region between 5 and 15 kpc, where σ stays constant up to 11 kpc and then decreases rapidly to follow the power law again, no shell feature can be identified in the simulations. We also see no signature of the bump in the corresponding density profile. Therefore, the deviation must have another origin and we call it the σ -bump. In the dark matter component, the velocity dispersion is much higher, following a power law without significant deviations, showing no signature of the σ -bump (see upper panel of Figure 1). The stellar components of our other nine galaxies also show a σ -bump (see Figure 2), including some simulations without gas or without a bulge. The mergers with mass ratio of 1:1 show a more prominent σ -bump than the mergers with mass ratio of 3:1. We therefore conclude that the σ -bump is a purely stellar feature common in our major merger sample and is dependent on the mass ratio of the progenitor galaxies.

The lower panel of Figure 1 shows the radial, tangential, and azimuthal components of the velocity dispersion of our example galaxy against radius. The σ -bump is most prominent in the azimuthal component, whereas for larger radii, the deviations from the power law are dominated by the radial component and therefore can be associated with the drift of the shell structures. A feature like the σ -bump, which is most prominent in the azimuthal component, could be caused by a disk structure embedded in the ETG.

In order to understand the origin of the σ -bump and to analyze its shape and size, we investigate the velocity dispersion at different time steps. The majority of our simulations run for 3.0 Gyr, with the merger taking place at about 1.5 Gyr for all galaxies; simulation 11 OBH 13 is run for 9.0 Gyr.

The upper panel of Figure 3 shows the stellar velocity dispersion of galaxy 11 OBH 13 at different times, indicated by different colors, from 1.7 Gyr (red curve) to 9.0 Gyr (black curve). The velocity dispersion of the progenitor spiral galaxy is included as a blue dotted line. The σ -bump is not present in the progenitor disks, but is a feature of the merger remnant alone. At the first time step shown, it is still forming, but from 2.0 Gyr onward, the σ -bump remains constant at all times, and thus differs clearly from all the other deviations present at larger radii, which vary or propagate outward and disappear after some



Figure 3. Upper panel: intrinsic stellar velocity dispersion of the example galaxy against radius, different colors indicate different time steps of the simulation (merger encounter at 1.5 Gyr), intrinsic stellar velocity dispersion of the progenitor spiral galaxy (blue dashed line). Lower panel: difference of the intrinsic stellar velocity dispersion to the corresponding power-law fit for different time steps (colors same as upper panel). (A color version of this figure is available in the online journal.)

time. This is emphasized in the lower panel of Figure 3, where the difference of the stellar velocity dispersion with respect to the power-law fit of the final time step is shown. Here, we can see more clearly that the σ -bump remains the same in size and shape, while the shell structures vanish with time.

4. COMPARISON TO OBSERVATIONS

To compare our results to observations, it is not sufficient to just consider the intrinsic stellar velocity dispersion, but also its projections. Figure 4 shows the line-of-sight velocity dispersion for different projections from face-on (0°) to edge-on (90°) in different colors against radius for our example galaxy, as well as the intrinsic velocity dispersion and its power-law fit. The σ -bump can be seen in all line-of-sight velocity projections, although with a somewhat lower relative amplitude, and should therefore be detectable by observations.

We compare our simulations with results from radial velocity measurements of PNe and red GCs in ETGs, as the red GCs are presumed to trace the field-star component of ETGs. We need these tracers to detect a decline in σ after 3 R_{eff} out to at least 4 R_{eff} , as stellar data do not provide this information. We use published position and velocity measurements to calculate the velocity dispersion as a function of radial distance. For most of the observed galaxies currently available, the observational data sets are not sufficient: either the total sample of tracers contains fewer than 200 objects, or the data mainly trace radii at which we do not expect to see the σ -bump.

Pota et al. (2013) recently published the kinematics of a sample of GCs in 12 ETGs from a spectroscopic survey (see also Strader et al. 2011; Arnold et al. 2011; Foster et al. 2011). The sample of PNe data from Coccato et al. (2009) is of similar size, but here we focus on the sample of Pota et al. (2013). We find a σ -bump in 4 of the 12 galaxies (NGC 821, NGC 1407, NGC 3115, NGC 4278) from this sample, while three other galaxies (NGC 3377, NGC 4365, and NGC 4494)

do not show a significant comparable feature but a constant or decreasing velocity dispersion. For the remaining five galaxies we cannot draw any firm conclusion as we are limited by low-number statistics (37 and 42 red GCs in NGCs 1400 and 2768, respectively, and 21 GCs in NGC 7457), the feature varies a lot with bin size (NGC 4486), or is observed at too large radii (NGC 5846). We include in Figure 4 the observed galaxies which most prominently show a σ -bump at the location of the σ -bump of our simulated galaxy 11 OBH 13.

For NGC 821, both PNe and red GCs trace a σ -bump behavior between 0.5 and 1.8 $R_{\rm eff}$ ($R_{\rm eff}$ = 5.79 kpc, PN data from Coccato et al. 2009, GC data from Pota et al. 2013, and stellar data from Proctor et al. 2009 and Forestell & Gebhardt 2010). It is an isolated E6 galaxy, with a velocity dispersion that generally shows a rapid decrease with radius (Romanowsky et al. 2003) and kinematic and photometric signatures of an edge-on stellar disk (Proctor et al. 2009).

The GC data of NGC 3115 were first presented by Arnold et al. (2011). This S0 galaxy contains a chemically enriched and kinematically distinct stellar disk (Norris et al. 2006). The σ -bump can be seen in the range of 0.7–2.2 $R_{\rm eff}$ ($R_{\rm eff} = 3.87$ kpc).

For NGC 4278 (GC data from Pota et al. 2013, stellar data from van der Marel & Franx 1993) we observe a σ -bump over a large range: from 1.5 to 3.8 R_{eff} (R_{eff} = 2.58 kpc). This galaxy has a large H I disk and a dusty patch (Goudfrooij et al. 1994).

We thus conclude that the σ -bump is a feature that can be observed with tracers in the outer parts of ETGs in the stellar component, given that a statistically significant number of tracers is available.

5. SUMMARY AND DISCUSSION

We have identified a new feature in the kinematics of ETGs, which can be seen in all spheroidals resulting from our sample of ten simulated isolated major mergers. The azimuthal



Figure 4. Upper left panel: stellar velocity dispersion against the radius of example galaxy 11 OBH 13—black line: intrinsic stellar component, black dashed line: power-law fit to intrinsic stellar component, dark violet: face-on projection, orange: edge-on projection, other colors: projections at different angles. Other three panels: observational data—upper right panel: NGC 4278, lower left panel: NGC 821, lower right panel: NGC 3115. GCs and PNe are shown by large symbols, additional stellar data by small symbols of the same kind and color (stellar data for NGC 821 from Forestell & Gebhardt 2010 (open diamonds) and Proctor et al. 2009 (filled diamonds), for NGC 3115 from Norris et al. 2006, for NGC 4278 from van der Marel & Franx 1993). We include the face-on and edge-on projections of the simulated example galaxy as dotted and dash-dotted lines.

(A color version of this figure is available in the online journal.)

component of the velocity dispersion contributes the most to the σ -bump, whereas shells are dominated by the radial dispersion component. This σ -bump can already be seen shortly after the merging event and remains stable with time, while other features such as shells vanish after a few Gyr. We found the σ -bump to be a purely stellar feature which is not mirrored by the velocity dispersion of the dark matter component. The σ -bump is most prominent in 1:1 mergers and therefore might be a signature of major mergers.

Observations of some ETGs such as NGC 821, NGC 1407, NGC 3115, and NGC 4278 show a positive deviation of the velocity dispersion in the same R_{eff} range as our galaxies. In two out of the three galaxies in Figure 4 (NGC 821 and NGC 3115), a stellar disk is observed, while the third galaxy (NGC 4278) has an H_I disk. All three galaxies are fast rotators (Emsellem et al. 2011; Pota et al. 2013).

The fact that the σ -bump is also present in galaxies which have been simulated without gas or bulge components suggests that it is a remnant of the kinematics of the disk stars of the progenitor galaxy. This is also supported by the fact that we do not see a bump feature in the blue GC component of the Galaxies from Pota et al. (2013). The region of the σ -bump is interesting, as it corresponds roughly to the size of the disk of the progenitor galaxy. Between 7 kpc and 14 kpc (23 kpc for 31 OBH 09 320), the dark matter begins to dominate over the stellar component, which might also influence the dynamics of the stellar component. The importance of the original orbit on which the two progenitor galaxies are set up also needs to be tested in further detail. The reasons for the presence or absence of the σ -bump thus remain to be investigated.

In a future study (A. T. P. Schauer et al., in preparation) we will investigate a larger sample of simulated galaxies, including

spheroidals from minor mergers and cosmological simulations, in order to survey if the σ -bump is present only in major mergers and how it relates to the disk of the progenitor galaxies. It is interesting that we also see a σ -bump in the Sbc dry merger with 0% gas by Dekel et al. (2005), but in none of their other mergers, and at least in one of the galaxies with mass ratio of 1:1 from Jesseit et al. (2007).

The velocity dispersion is a quantity for which the accuracy strongly depends on the number of observed tracer objects. To understand which signatures about the formation history and evolution of ETGs are retained by their outer halos, more detailed observations of the outskirts of ETGs are required, especially larger observational tracer samples.

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