Connecting traces of galaxy evolution: the missing core mass – morphological fine structure relation

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ABSTRACT

Deep exposure imaging of early-type galaxies (ETGs) are revealing the second-order complexity of these objects, which have been long considered uniform, dispersion-supported spheroidals. “Fine structure” features (e.g. ripples, plumes, tidal tails, rings) as well as depleted stellar cores (i.e. central light deficits) characterize a number of massive ETG galaxies, and can be interpreted as the result of galaxy-galaxy interactions. We discuss how the timescale for the evolution of cores and fine structures are comparable, and hence it is expected that they develop in parallel after the major interaction event which shaped the ETG. Using archival data, we compare the “depleted stellar mass” (i.e. the mass missing from the depleted stellar core) against the prominence of the fine structure features, and observe that they correlate inversely. This result confirms our expectation that, while the Super Massive Black Hole (SMBH) binary (constituted by the SMBHs of the merger progenitors) excavates the core via three-body interactions, the gravitational potential of the newborn galaxy relaxes, and the fine structures fades below detection levels. We expect the inverse correlation to hold at least within the first Gyr from the merger which created the SMBH binary; after then, the fine structure evolves independently.

Key words: galaxies: bulges — galaxies: elliptical and lenticular, cD — galaxies: evolution — galaxies: photometry — galaxies: structure

1 INTRODUCTION

Owing to the development of advanced instrumentation during the last decades, we are realizing that early-type galaxies (ETGs) deviate from the iconic picture of a perfectly spheroidal and dynamically relaxed system. For example, integral field unit surveys such as SAURON (e.g. Cappellari et al. 2007; Emsellem et al. 2007) and ATLAS3D (Cappellari et al. 2011) recently showed that ETGs are not purely “dispersion supported” systems (i.e. their stars only follow disordered orbits), but also present a rotational component.

Higher-order characteristics of ETGs represent precious information which potentially allow to address the different patterns which lead to their formation, within the widely supported scenario of hierarchical galaxy evolution (e.g. White & Rees 1978; Springel et al. 2005; Hopkins et al. 2006, 2010, and references therein), in which elliptical galaxies are the end-products of violent galaxy interactions. In this work we concentrate in particular on two attributes of ETGs: fine structures and depleted stellar cores.

Fine Structures

Fine structures are extremely faint (24–27 mag/arcsec²; e.g. Duc et al. 2011) features which manifest in ETGs as a mixed collection of morphological structures, including e.g. ripples, plumes, tidal tails, “boxy” isophotes, or rings. Such features, originally identified by Schweizer & Seitzer (1988) as a peculiarity of a few objects, are now recognized to be ubiquitous once an appropriate image depth is reached (e.g. Duc et al. 2011; Spavone et al. 2017). Fine structures depict the remnants of the last interaction which shaped the observed morphology of the galaxy, and are expected to fade out
progressively as the gravitational potential relaxes (Barnes 1988; Hernquist & Quinn 1988, 1989). They therefore represent a unique tool for studying galactic archaeology, and are ideal to investigate the history of dry (i.e. relatively gas-free) mergers, where the lack of star-formation limits the possibility to estimate the time elapsed from the event. The seminal papers on the subject could be considered the works by Schweizer et al. (1990) and Schweizer & Seitzer (1992), in which the authors provide a semi-empirical definition of a “fine structure parameter” $Z$, which they visually estimated on unsharpmasked images by identifying the number and/or strength of structures. Currently, several projects are creating extended, deep mosaics of nearby galaxies with the ultimate intent of studying the traces of interactions and low-brightness galaxy satellites, such as e.g. the Next Generation Virgo Cluster Survey (NGVS; Ferrarese et al. 2012), the Fornax Cluster Deep Survey (FCDS; e.g. Iodice et al. 2016), the Mass Assembly of early-Type GaLAXies with their fine Structures (MATLAS; P.I.: P.A. Duc), or the VST survey of Early-type Galaxies in the Southern hemisphere (VEGAS; P.I.: E. Iodice).

**Depleted Stellar Cores**

Luminous ($M_b < -20.5$ mag) ETGs present one additional idiosyncrasy which distinguishes them from the smaller-mass ones: they are characterized by the presence of a “core”, i.e. a central luminosity deficit (not due to dust obscuration) with respect to the inward extrapolation of the outer light profile (e.g. Lauer 1985).

According to the generally accepted scenario, depleted stellar cores are thought to be related to the dry merger of galaxies. In this context, the Super Massive Black Holes (SMBHs) at the center of each of the merging progenitor are dragged by dynamical friction towards the center of the gravitational potential and eventually form a SMBH binary at the center of the merger remnant. The basic idea is that three body interactions between the stars and the SMBH binary transfer energy to the stars, hence ejecting them from the center of the newly formed galaxy, creating the central stellar mass deficit (Begelman et al. 1980). This hypothesis is supported by the observed scaling relations between the SMBH mass and the core size or the “missing stellar mass” (e.g. Lauer et al. 2007; Dullo & Graham 2014). The energy is transferred to the interacting stars at the expense of the SMBH binary, whose orbital separation shrinks along the process, leading the binary to coalescence while the core is excavated.

An important caveat is that the SMBH binary scouring is not expected to happen in a gas-rich environment. In fact, in this case the gas would disperse a significant fraction of the energy of the SMBH binary in lieu of the stars. Moreover, any excavated core could be replenished by central star formation (e.g. Mihos & Hernquist 1994; Barnes & Hernquist 1996; Hopkins et al. 2008, 2009). This caveat is consistent with the observation that core galaxies are almost exclusively radio-loud objects (e.g. Capetti & Balmaverde 2005, 2006, 2007; Richings et al. 2011), given that radio-loud AGNs are long thought to be cold-gas starved systems in a low activity state (e.g. Best et al. 2006).

In this context, the amount of missing stars — or “mass deficit” — can be quantified from the difference between the extrapolation of the outer radial profile (indicative of the pristine galaxy) and the observed profile (with an excavated core; see panel C-2 in Figure 1). The surface brightness profile of the spheroidal component of galaxies hosting a core can in fact be described by a smooth connection between an inner power-law and an outer Sérsic function (the “core-Sérsic model”; Graham et al. 2003).

We have therefore a coherent theoretical framework — the hierarchical merging scenario — able to simultaneously explain: 1) the emergence of fine structure features in post-merger massive galaxies, 2) the excavation of stellar cores, and 3) the merging of SMBH binaries at their centers. What was still lacking, is a coherent observational investigation which would ultimately connect the merger history of massive ETGs with the fine structure, prominence of core, and central SMBH.

With the present work, we demonstrate that these aspects are indeed intimately connected. In §2 we discuss how the timescale for the creation of the core and the disappearance of fine structures are consistent, in §3 we present observational results supporting the core – fine structure connection, in §4 we discuss our interpretations, while we in §5 we summarize our results.

## 2 Timescale Considerations

According to the hierarchical galaxy formation scenario, massive ETGs are mostly assembled through mergers, whose traces — the residual fine structure features — progressively fade out with time. At the same time, in the case a dry merger event, a core is excavated by a coalescing SMBH binary at the center of the newly formed galaxy. How do the timescale of these two processes compare?

In a recent numerical simulation, Khan et al. (2012a) showed that (at least in the case of minor mergers of disk galaxies) SMBHs with masses $10^6-10^7 M_\odot$ will completely coalesce within 1–2 Gyr after the merger. This figure encompasses the whole time span from the merger to the actual SMBH merger. In a related simulation, the same authors (Khan et al. 2012b) showed that, while the total coalescence time is ~2.9 Gyr, the SMBH scouring phase lasts ~1 Gyr (after which the SMBH pair rapidly merges via gravitational wave emission). In general, there seems to be consensus on that, in dry mergers, the scouring phase alone can last a few Gyr (for a review, see Colpi 2014).

On the other hand, the average survival time of fine structures is a parameter much more difficult to estimate; simulation-wise because it requires to reproduce a great variety of features, and observationally-wise because of the low surface brightness of the structures compared to the main body of the galaxy. Despite of the obstacles, the literature regarding simulations aimed at interpreting the interaction and merger debris is rich. The variety of these idealized simulations yielded diverse results, but estimations of survival times in both the spatial– and the phase–space agree in that fine structures should remain coherent for at least 1 Gyr (e.g. Hibbard & Mihos 1995; Feldmann et al. 2008; Johnston et al. 2001, 2008; Michel-Dansac et al. 2010; Peirani et al. 2010; Torrey et al. 2015; Duc 2016). Studying color differences between the fine structures and the host galaxy, Schweizer & Seitzer (1992) estimated the average survival time to 1–2 Gyr. Using a wider sample and deeper exposures, Duc et al. (2011) argue that, although an upper limit could be
set at 5 Gyr, the vast majority of the collisional debris would fall back onto the main body of the galaxy within a couple of Gyr (e.g. Hibbard & Mihos 1995). The aforementioned studies additionally show that the specific timescale clearly depend upon the type of merger which generated a given fine structure. Structures predominantly associated with “wet” (i.e. gas rich) events, such as tidal tails and plumes, are relatively short-lived (1–2 Gyr), while structures potentially associated with dry mergers such as shells (e.g. Paudel et al. 2017) could survive up to 4 Gyr.

Thus, the theoretically estimated timescale for the merger remnants fine structures to significantly [if not completely] fade out is at least sufficiently large to complete the formation of cores through SMBH scouring. In other words, it is expected that fine structure coexists with SMBH binaries at different stages in their process of excavating the core. In fact, the two processes should initially advance in parallel: while the SMBH binary (created soon after the merger event) proceeds with its scouring action, the fine structure features gradually disappear due to the relaxation of the gravitational potential. Since however the fine structure life span is on average larger than the timescale of core excavation, at some point this co-evolution could cease. After about ~1 Gyr, while the core will not expand significantly, the galaxy will still keep reducing its fine structure.

3 MEASUREMENTS OF CORES AND FINE STRUCTURES

We defined a sample of nearby ETGs galaxies, for which we could retrieve literature values for both the fine structure and the stellar mass deficit. The “bottleneck” for this selection was dictated by the scarcity of studies reporting numerical evaluations of diverse fine structures. For our purpose, we used the semi-quantitative “fine structure parameter” (Σ) defined by Schweizer et al. (1990), see §1. We additionally considered the “tidal parameter” (Tc) by Tal et al. (2009), which however represents a simplified statistics based on the presence of distortions on the residual images after subtracting a [symmetric] galaxy model, similarly to the only other studies we are aware of, nominally van Dokkum (2005) and McIntosh et al. (2008). We stress that, despite of its name, the tidal parameter does not exclusively describe “tidal tails”, but dishomogeneities in general (see Equations 1 and 2 of Tal et al. 2009).

For the 69 objects in Schweizer et al. (1990), we searched in the literature for core-Sérsic fits to their surface brightnesses, and found 19 among the samples of Richings et al. (2011) and Dullo & Graham (2014). Of those galaxies, 14 display fine structure (Σ > 0); these objects represented the primary sample for the current study (9 have core parameters from Dullo & Graham 2014, 7 from Richings et al. 2011, 2 are in common). The remaining 5 galaxies did not present any evident structure (Σ = 0); we used this as a comparison sample, keeping in mind that the lack of structure might be due to the limited sensitivity of the data used in Schweizer & Seitzer (1992, 40–60 min exposure images from the 0.9 m KPNO telescope), rather than an intrinsic feature. Our small sample is representative of the range of Σ in Schweizer et al. (1990), and of the depleted mass in typical core galaxies. Similarly, the sub-sample of 52 galaxies by Tal et al. (2009) with disturbed morphology (Tc > 0) was cross-correlated against Dullo & Graham 2014 and Richings et al. 2011, obtaining 6 and 2 matches, respectively (1 in common). In this case, the comparison sample of featureless objects (Tc = 0) consisted only in one, common galaxy.

We calculated the spheroid mass (M_{sph}): mass associated to the “bulge” of the galaxy, excluding any disk structure) by integrating the core-Sérsic profiles by Dullo & Graham 2014 and Richings et al. 2011 to obtain the total luminosity, and then converting to stellar mass by assuming a mass-to-light ratio for a uniformly old (12 Gyrs), solar metallicity stellar population (as appropriate for massive early-type galaxies, e.g. Gallazzi et al. 2006) To derive our mass-to-light ratios we used the “Worthey model interpolation engine” applet¹ based on the evolutionary models by Worthey (1994), where we adopted the default Salpeter initial mass function prescriptions. Similarly, the mass deficit (M_{def}) was inferred from the difference between the full core-Sérsic profile, and the extrapolation of its Sérsic part (the latter being indicative of the pre-depletion profile; Graham et al. 2003) — see side panels in Figure 1.

In the central panels of Figure 1, we show the fine structure parameter (panel B-1) and tidal parameter (panel B-2) as a function of the mass deficit normalized by the spheroid mass (M_{def}/M_{sph}). The scatter in the plots is due to the uncertainty on both quantities:

1) The parametrisation of fine structure is the main source of uncertainty, due both to the lack of a robust definition, and to the dependence of Σ (or Tc) on the image data quality and depth. A good example is NGC 5557, for which Schweizer et al. (1990) reported Σ = 2.87, while more recent and deeper observations revealed additional structure, raising Σ to 6.00 (Duc et al. 2011). Such depth biases are expected to similarly affect all data points, hence maintaining the observed distribution. Moreover, one can reasonably assume that any present structure was detected with similar efficiency within the Schweizer et al. (1990) or Tal et al. (2009) samples, except possibly for the Σ = 0 (Tc = 0) galaxies (as discussed above).

2) There is often a significant mismatch in the recovered depleted mass due to differences in fitting techniques. For the galaxies they have in common (other than the ones shown in Figure 1), the mass deficit derived from Richings et al. (2011) and Dullo & Graham (2014) differ on average by ~40%.

In the same panels, we show with a solid pink line a linear fit to the Σ > 0 and Tc > 0 samples, respectively of the form:

Σ = c_Σ + m_Σ × log(M_{def}/M_{sph})
(1)

Tc = c_T + m_T × log(M_{def}/M_{sph})
(2)

which yielded the best-fit parameters c_Σ = −0.10 and m_Σ = −1.30, and c_T = 0.03 and m_T = −0.02. These fits have been weighted by the reliability of the core measurement, with the weights estimated as the ratio between the core size and the seeing FWHM of the relevant observation. In order to exclude the possibility that the 2 highest Σ galaxies (nominally

¹ http://astro.wsu.edu/worthey/dial/dial_a_model.html
NGC 3640 and NGC 4382 drive the relation, we applied a 2-points bootstrapping. In practise, we devised an iterative procedure in which two random points were removed from the sample at each iteration and the fit was re-performed, until all possible combinations were covered. For $T_c$ we performed a similar test, but adopting a 1-point bootstrapping, given the smaller number of data. This analysis yielded a range of best-fit relations which span within the the shaded pink area in panels B-1 and B-2, representative of the error on our best-fits. Additionally, we calculated the Pearson correlation coefficient for the fit of Equation 1, obtaining $R = -0.71$ and $-0.44$ for the full sample and after excluding the 2 points with the largest $\Sigma$, respectively. For the fit of Equation 2, we obtained $R = -0.85$ and $-0.75$ for the full
sample and after excluding the point with the largest \( T_c \), respectively. A test based on the Fisher \( z \) transformation showed that, for both fits, the Pearson coefficients obtained with the full or the reduced samples are consistent within the 95\% confidence level. This indicates that there is no significance difference by excluding the aforementioned 2 \( (1) \) data points, and further confirms the solidity of the linear relations.

As a further test of our analysis, we wanted to check if galaxies which have not yet developed a core consistently present high levels of fine structure. Richings et al. (2011), apart from the core-Sérsic galaxies we referred up to now, also reported 41 objects whose spheroidal component was successfully fit with a simpler Sérsic profile; this implicitly classifies them as core-less. However not all core-less galaxies are suitable to our test: we need to select only those which are indeed “pre-destined” to develop a core, but were by chance observed very early in their formation, and hence only momentarily appear as Sérsic because they did not develop yet an measurable core. Core-less galaxies however include also “pure” Sérsic galaxies, which will never develop a core because their formation e.g. involved significant gas fractions — these are contaminant objects we want to segregate. Lacking an age estimation, one indicative way to select “pre-destined” core galaxies is to adopt the magnitude limit: it is in fact observed that ETG brighter than \( M_B \approx -20.5 \) mag are statistically prone to present cores (e.g. Kormendy et al. 2009; Graham 2013, and references therein). We therefore applied this magnitude cut to the core-less Richings et al. (2011) galaxies with a measured \( \Sigma \) (or \( T_c \)), resulting in the selection of NGC 0474 and NGC 4125\(^2\). Such a small number of matching objects (2 out of the parent 41) was indeed expected since observing a core-Sérsic galaxy soon after its formation is a statistically rare occurrence: the vast majority core-less objects are “pure” Sérsic galaxies. These two objects appear in panel B-1, where their mass deficit has been set to an arbitrarily small value. Under the assumption that NGC 0474 and NGC 4152 are in-the-making core galaxies, their location in the plot is consistent with our evolutionary scenario.

Notice that the overall \( \Sigma \) value does not distinguish between features primarily associated with gas-rich interactions and star-formation (e.g. tidal tails and streams) and those potentially associated with gas-poor mergers and/or no star-formation (e.g. shells), despite its numerical value is more biased towards shell structures (see formulation in Schweizer et al. 1990). For our study, we are in principle interested in fine structures not associated with gas infall since this would hamper the formation of a depleted core (see §1). To exclude the possibility that the fine structures of the core galaxies in our sample were associated with significantly gas-rich mergers, we visually inspected SDSS-DR13 images of the sample galaxies using the “SDSS Navigator” applet\(^3\). We found that the only fine structures presented by the galaxies were shells, with the exception of NGC 4552 and NGC 5557, which also presented plumes. This observation also suggests that the galaxies considered here underwent similarly gas-abundant mergers, and in turn it supports the implicit assumption that the significance of fine structure monotonically declines in time.

4 DISCUSSION

In the recent years, alternative formation scenarios for the excavation of a core have been promoted. The need for alternative models arose partly to explain the observation of a growing number of objects with extremely large cores (> 1 kpc; e.g. Hyde et al. 2008; Postman et al. 2012; López-Cruz et al. 2014; Dullo et al. 2017) which would imply extremely large depleted masses. In Bonfini & Graham (2016) we calculated that as much as \( 10^{11} \) \( M_\odot \) have been displaced from the center of the Brightest Cluster Galaxy (BCG) of Abell 2261, and created a 3.6 kpc core, much more than what simulations predict for SMBH binary scarring (Merritt 2006).

As a corollary to the binary SMBH scenario, it has been suggested that — after coalescing — the merged SMBH will receive a kick due to the anisotropic emission of gravitational waves: this might explain larger cores. In fact, the displacement of the merged SMBH transfers large amounts of energy to the surrounding stars, and this might not only directly generate a core (e.g. Merritt et al. 2004; Boylan-Kolchin et al. 2004), but also significantly enlarge an existing one, possibly by multiple oscillations (Gualandris & Merritt 2008; Lena et al. 2014). Among the emerging alternative scenarios, there is also the “AGN feedback” mechanism proposed by Martizzi et al. (2012), and the core excavation by an in-falling, captured perturber (e.g. Goerdt et al. 2010; Petts et al. 2015). The latter was actually proposed to explain the formation of constant density cores in dark matter halos, but in Bonfini & Graham (2016) we proved it could also be applied to the study of extremely large baryonic cores.

However — although few exceptional cases might require alternative models — the SMBH scenario is still the most favoured due to the extended theoretical support, and the existence of scaling relations between the core properties and the SMBH mass (e.g. Lauer et al. 2007; Dullo & Graham 2014). There are also growing observational indications for SMBH pairs at the kpc scale, observed at the center of merger remnants (e.g. NGC 6240, Komossa 2003; Arp 299, Ballo et al. 2004; 0402+379, Rodriguez et al. 2006; Mrk 463, Bianchi et al. 2008). The recent “visual” detection of a binary whose SMBHs are separated by a projected distance of

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\(^2\) We excluded NGC 5982 for coherency, being one of the few objects for which Richings et al. 2011 did not report a distance, although the distance retrieved from NED technically makes this object part of the selection.

\(^3\) skyserver.sdss.org/dr13/en/tools/chart/navi.aspx
only ~7 pc poses the strongest observational confirmation so far (Bansal et al. 2017). At the same time, we are aware that galaxies with the largest cores (> 1 kpc) also host the most massive SMBH in the Universe, plausibly produced by a coalesced binary (e.g. Laine et al. 2003; Lauer et al. 2007). The recent, direct detection of gravitational waves in stellar-sized merging black holes (Abbott et al. 2016a,b,c, LIGO collaboration) arguably constitutes the strongest evidence of black hole coalescence (even if at a smaller mass scale).

Our results provide additional support to the SMBH scavenging scenario. The linear relation in the central panels of Figure 1 shows clear indication that the significance of fine structures scales inversely to the relative depleted mass over 4 orders of magnitude in $M_{def}/M_{sph}$. Remarkably, galaxies which will eventually develop a core (see NGC 4125 and NGC 0474 in panel B–I) consistently present indication of prominent fine structure. This strongly suggests that galaxy relaxation and core excavation are indeed happening in parallel. Once the core is almost completely excavated and the SMBH binary coalesced (1 Gyr), a galaxy stops moving diagonally along the relation and it starts moving vertically down until the complete disappearance of fine structures (which could take up to 4 Gyr). This evolutionary track is represented in the central panel of Figure 1 with grey arrows. The observation that no galaxy with large $M_{def}/M_{sph}$ presents significant fine structure, and that all featureless galaxies have large $M_{def}/M_{sph}$, is coherent with this picture.

The observed trend is instead at odds with stochastic core depletion events, like the capture of an in-falling satellite (e.g. Goerdt et al. 2010). On the contrary, a larger core would require a larger satellite infall, which in turn would produce larger fine structures. The considerations about the AGN-feedback scenario (e.g. Martizzi et al. 2012) are instead more complex. In the first place, AGN activity acts on a way smaller temporal scale ($\sim 10^7$; Kauffmann & Haehnelt 2000; Hopkins et al. 2005) than fine structure evolution. Outflows are impulsive and might produce a core of arbitrary size at any stage of the galaxy life. Secondly, focusing on the objects in our analysis, we exclude that they involved large gas fractions ($\delta$), hence we do not expect a significant AGN feedback able to justify the creation of the largest cores in our sample. As a matter of fact, the Martizzi et al. (2012) mechanism has been proposed for BCGs, in which the large cool inflow of cluster gas can explain extreme accretion events. Finally, one could argue that large depleted mass would imply a strong AGN activity, which in turn requires significant gas infall on the SMBH which is more prone to happen when the gravitational potential is not relaxed yet, i.e. right after the merger, when $\Sigma$ is still large (at odds with Figure 1). Furthermore, it has also been questioned whether merger events are associated with a higher AGN activity in the first place (Li et al. 2008).

5 CONCLUSIONS

We promote the idea that depleted stellar cores in ETGs are progressively excavated in parallel with the disappearance of the fine structure features (remnant of the last major interaction experienced by the galaxy). This prediction is in line with the expectations from the hierarchical formation scenario of galaxies, and with the SMBH mechanism for core depletion.

We observe that the timescale for core excavation and relaxation of the galaxy potential are similar or in excess of 1 Gyr (from the merger event which assembled ETG), hence large enough for the two processes to initially co-evolve. We show observational evidence that the prominence of fine structure anti-correlates with the amount of mass removed from the core (normalized by the total mass of the host galaxy). We argue that this anti-correlation shall hold at least within the first Gyr from the assembly of the galaxy (i.e. until the core is fully developed), after which time the fine structure evolves independently. Our results support the SMBH scavenging as the main channel (although not necessarily the only one) for the formation of depleted stellar cores.

Deep follow up of ETGs known to host cores will allow to better constrain the relation presented in Figure 1, and to reduce the systematic uncertainties due to the parametrisation of the fine structure. By properly quantifying fine structures, and by calibrating them against numerical simulations, one will be able to replace the fine structure measurement (the y-axis) with a time proxy. By interpreting Figure 1 in this way, our approach will therefore represent a sophisticated method to exploit the structure of galaxies to estimate the age of a merged ETG, overcoming the known measurement limitations related to their uniformly old stellar populations.

ACKNOWLEDGEMENTS

The authors wish to thank the anonymous referee for the detailed comments which significantly helped to strengthen our conclusions. TB would like to acknowledge support from the CONACyT Research Fellowships. OGM wishes to acknowledge support by the UNAM PAPIIT grant (IA100516 PAPIIT/UNAM).

REFERENCES

Abbott B. P., et al., 2016a, Physical Review Letters, 116, 061102
Abbott B. P., et al., 2016b, Physical Review Letters, 116, 241103
Abbott B. P., et al., 2016c, Physical Review Letters, 118, 221101
Ballo L., Braitot V., Della Ceca R., Maraschi L., Tavecchio F., Dadina M., 2004, ApJ, 600, 634
Bansal K., Taylor G. B., Peck A. B., Zavala R. T., Romani R. W., 2017, preprint, arXiv:1705.08556
Barnes J. E., 1988, ApJ, 331, 699
Barnes J. E., Hernquist L., 1996, ApJ, 471, 115
Begelman M. C., Blandford R. D., Rees M. J., 1980, Nature, 287, 307
Best P. N., Kaiser C. R., Heckman T. M., Kauffmann G., 2006, MNRAS, 368, L67
Bianchi S., Chiaberge M., Piconcelli E., Guainazzi M., Matt G., 2008, MNRAS, 386, 105
Bonfini P., Graham A. W., 2016, ApJ, 829, 81
Boylan-Kolchin M., Ma C.-P., Quataert E., 2004, ApJ, 613, L37
Capetti A., Balmaverde B., 2005, A&A, 440, 73
Capetti A., Balmaverde B., 2006, A&A, 453, 27
Capetti A., Balmaverde B., 2007, A&A, 469, 75
Cappellari M., et al., 2007, MNRAS, 379, 418
Cappellari M., et al., 2011, MNRAS, 413, 813
Colpi M., 2014, Space Sci. Rev., 183, 189
