THE IMPRINT OF MASSIVE BLACK HOLE MERGERS ON THE CORRELATION BETWEEN NUCLEAR STAR CLUSTERS AND THEIR HOST GALAXIES

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ABSTRACT

A literature compilation of nuclear star cluster (NSC) masses is used to study the correlation between global and NSC properties. A comparison of observational data to the predictions of semi-analytical galaxy formation models places constraints on the co-evolution of NSCs, massive black holes (MBHs), and host galaxies. Both data and theoretical predictions show an increased scatter in the NSC scaling correlations at high galaxy masses, and we show that this is due to the progressively more efficient ejection of stars from NSCs caused by MBH binaries in more massive stellar spheroids. Our results provide a natural explanation of why in nucleated galaxies hosting an MBH, the ratio \( \frac{M_{\text{NSC}} + M_{\text{MBH}}}{M_{\text{bulge}}} \) (with \( M_{\text{bulge}} \) as the host spheroid’s mass) shows significantly less scatter than \( \frac{M_{\text{NSC}}}{M_{\text{bulge}}} \), and suggest that the formation of MBHs and NSCs are not mutually exclusive, as is also supported by observations of co-existing systems. Both MBHs and NSCs represent generic products of galaxy formation, with NSCs being destroyed or modified by the merger evolution of their companion MBHs.

Key words: galaxies: evolution – galaxies: formation – galaxies: nuclei – Galaxy: center

1. INTRODUCTION

Observations over the last two decades have unveiled the existence of compact stellar nuclei at the centers of most intermediate- and low-luminosity galaxies (Carollo et al. 1998; Böker et al. 2002; den Brok et al. 2014; Georgiev & Böker 2014). With masses of order of 0.1% of the stellar mass of the host galaxy and typical radii of only a few parsecs, these clusters, often referred to as nuclear star clusters (NSCs), are the densest stellar systems observed in the universe (e.g., Walcher et al. 2005; Côté et al. 2006; Carson et al. 2015).

The masses of NSCs \( (M_{\text{NSC}}) \) obey fairly tight correlations with properties of the host galaxies such as the bulge velocity dispersion \( (\sigma) \) and mass \( (M_{\text{bulge}}) \) (Ferrarese et al. 2006a). A number of authors have shown that there are correlations, where mass is shallower than the corresponding ones for massive black holes (MBHs). Graham (2012a) finds that NSC masses obey \( M_{\text{NSC}} \sim \sigma^{2} \), while the masses of MBHs, \( M_{\text{MBH}} \), follow a much steeper scaling relation, \( M_{\text{MBH}} \sim \sigma^{5} \) (Ferrarese & Ford 2005). It is intriguing that for galaxies containing both an NSC and an MBH, the ratio \( \frac{M_{\text{NSC}} + M_{\text{MBH}}}{M_{\text{bulge}}} \) (with \( M_{\text{CMO}} = M_{\text{MBH}} + M_{\text{NSC}} \) as the total mass in central massive objects) shows less scatter than either \( \frac{M_{\text{MBH}}}{M_{\text{bulge}}} \) or \( \frac{M_{\text{NSC}}}{M_{\text{bulge}}} \) (Kormendy & Ho 2013). The fact that both NSCs and MBHs are found to follow tight correlations with their host-galaxy properties, that they are found to coexist in some galaxies, and that in these galaxies they have comparable masses, points toward a picture where NSCs and MBHs are both generic byproducts of galaxy formation, and the growth mechanisms of NSCs and MBHs are related to one another and to the host-galaxy evolution.

We have developed a semi-analytical model following the formation and evolution of galaxies, MBHs, and NSCs along cosmic history. Previous calculations assumed NSC formation to take place in isolated galaxies (e.g., Agarwal & Milosavljević 2011; Antonini 2013; Gnedin et al. 2014; Arca-Sedda & Capuzzo-Dolcetta 2014; Aharon & Perets 2015), thus neglecting the possible role of galaxy mergers, as well as in situ star formation processes. Also, these early idealized attempts did not explore the possible interplay between MBH and NSC evolution. Our model sheds light on exactly these points, i.e., it allows us to assess for the first time the role of galaxy mergers, MBH mergers, and nuclear star formation on the formation and evolution of NSCs.

2. METHOD AND MODEL

The backbone of this study is the semi-analytical galaxy formation model of Barausse 2012; with the improvements described in Sesana et al. 2014). This model tracks the evolution of baryonic structures (both in central galaxies and in satellites) along dark matter merger trees produced with an extended Press–Schechter formalism, modified to reproduce the results of N-body simulations of dark matter halos (Parkinson et al. 2008). The baryonic structures ultimately originate from the hot, largely unprocessed intergalactic medium, which cools to form cold gaseous galactic disks. These structures undergo quiescent star formation, which chemically enriches the interstellar medium and gives rise to stellar disks. Both stellar and gaseous disks are disrupted by bar instabilities—giving rise to pseudo-bulges that undergo a quiescent disk-like star formation process—and by major mergers that form classical bulges with violent star formation bursts, possibly triggered by turbulent gas flows. Besides further enriching the interstellar medium, bar instabilities and (mainly) starbursts are assumed to funnel cold, chemically enriched gas into a low angular momentum nuclear reservoir, available for accretion onto the central MBH (Granato et al. 2004; Haiman et al. 2004). Possible mechanisms capable of removing angular momentum from the gas are shocks (caused, e.g., by mergers) or radiation drag from starbursts (Umemura...
expressions for \( a_h \) and \( a_{gr} \) in Merritt (2013), \( V_{\text{kick}} \) the post-merger kick velocity (computed using the fit to numerical-relativity simulations presented in van Meter et al. 2010), and \( V_{\text{esc}} \) the escape velocity from the central parts of the galaxy (computed using the bulge and NSC density profiles).

The first term in Equation (1) accounts for the mass deficit before the MBH binary becomes hard (Merritt 2006); the second is the mass ejected from \( a_h \) to \( a_{gr} \); the third represents the mass deficit generated as the kicked MBH heats up the surrounding core (Gualandris & Merritt 2008).

We also account for the tidal disruption of NSCs by MBHs during galaxy mergers. More precisely, in a merger between a galaxy containing an MBH and one containing only an NSC, the NSC is tidally disrupted before reaching the center of the newly formed galaxy if the MBH mass is \( \gtrsim 10^{8-9} M_\odot \). This is the same process described above for the infall of stellar clusters.

Next, we present our model’s predictions, with the free parameter \( f_{gr} \) set to its Milky Way value, i.e., \( f_{gr} \approx 0.07 \) (Kuijssen 2012). We have checked the robustness of our results against the MBH seed model (i.e., light versus heavy seeds, with several halo occupation numbers), a different value for \( f_{gr} \leq 0.2 \), a variable \( f_{gr} \) (set to 0.07, 0.04, and 0.5 in disk, quiescent, and starburst galaxies, respectively; Kuijssen 2012), and other details of our model (i.e., merger-tree resolution, initial redshift of the simulations, active galactic nucleus (AGN) feedback prescriptions, etc.). Indeed, we will show that the crucial ingredient to reproduce the observed global to NSC correlations is the scouring effect due to MBH binaries described by Equation (1). More details of our model will be presented elsewhere (F. Antonini et al. 2015, in preparation).

We describe the results from two realizations of our galaxy formation model, namely, our fiducial model, which accounts for the “NSC erosion” due to MBH binaries through Equation (1) and the “NSC preservation” model where that effect is absent (i.e., we set \( \dot{M}_{\text{ej}} = 0 \) throughout the entire cosmic history).

Our model’s results are compared to a literature compilation of NSC masses. We constructed our sample of NSC objects by combining data from Table 1 of Scott & Graham (2013), Table 2 of Erwin & Gadotti (2012), Table 2 of Neumayer & Walcher (2012), and by estimating NSC masses for the early-type galaxies in the Fornax cluster catalog of Turner et al. (2012). The masses of the NSCs in the Turner et al. (2012) sample were calculated from the \((g - z)\) colors given in that paper and from the relations of Bell et al. (2003). The galaxy velocity dispersion and bulge mass were also obtained from these papers or, when not available, from the Hyperleda database (Paturel et al. 2003).

The upper panels of Figure 1 compare the observed \( M_{\text{NSC}} - \sigma \) and \( M_{\text{NSC}} - M_{\text{bulge}} \) relations to our “NSC erosion” model. We note the excellent agreement of our predictions with observations. In particular, the predicted scaling relations appear to broaden at higher velocity dispersion, as do the data. The broadening of the data appears to be caused by the subsample of galaxies with determined MBH mass (red points in Figure 1). The nuclear to global correlations in these galaxies appear to flatten or even decline for spheroids with higher velocity dispersion, suggesting that the MBHs have played an important role.
role in affecting the properties of their host NSCs in these galaxies.

The blue lines in the middle panels of Figure 1 show the scaling relations obtained from the "NSC preservation" model. Note that the broadening at high σ present in the upper panels disappears. This demonstrates that the broadening of the scaling relations seen in the "NSC erosion" model is a consequence of dynamical ejection of stars from coalescing MBH binaries. Together with the model’s predictions, we plot $M_{\text{CMO}} = M_{\text{NSC}} + M_{\text{MBH}}$ versus $\sigma$ and $M_{\text{bulge}}$ for nucleated galaxies with a measured MBH mass or an upper limit to it. MBH masses and upper limits were taken from Table 1 of Erwin & Gadotti (2012), Table 2 of Neumayer & Walcher (2012), and Table 1 of Graham & Spitler (2009). The red lines show fits to these data. As can be seen, when the disruptive effect of MBH binaries is not included, our model recovers the fitted functional form of the relation between $M_{\text{CMO}}$ and galaxy properties, both in slope and normalization.

The fact that our “NSC preservation” model predicts scaling correlations that are consistent with relations involving $M_{\text{CMO}}$ is not coincidental, but rather quite revealing. Indeed, the mass ejected by an MBH binary is of the order of the mass of the binary itself, with only a weak dependence on the binary’s mass ratio and the initial density distribution of stars (Merritt &...
Szell 2006). Hence, the mass ejected in N MBH mergers is approximately \( M_{\text{ej}} \approx N M_{\text{MBH}} \), with \( M_{\text{MBH}} \) as the final MBH mass.

Because infall of gas to the nuclear region can rapidly rebuild an NSC, the relevant quantity to estimate is the number of MBH mergers since the era at which most of the gas was depleted from the galaxy. Haehnelt & Kauffmann (2002) compute this quantity using semi-analytic models for galaxy mergers similar to ours. They find that the number of comparable-mass MBH mergers is weakly dependent on galaxy luminosity and has a small dispersion around a median of 1, with values \( \leq 4 \) even for the most luminous galaxies. Accordingly, derived mass deficits in “core galaxies” are also found to be peaked around a value of \( \approx M_{\text{MBH}} \) (Graham 2004).

The total amount of ejected stellar mass is therefore determined mainly by, and is roughly equal to, \( M_{\text{MBH}} \). Therefore, \( M_{\text{CMO}} = M_{\text{NSC}} + M_{\text{MBH}} \) can be regarded as an approximate estimate (with uncertainties of the order a few) of the NSC mass that was in place before mass erosion due to MBH binaries became important. Our models do indeed confirm this.

These facts explain why the “NSC preservation” model predicts scaling correlations that are consistent with relations involving \( M_{\text{CMO}} \) and provide further support for the idea that the broadening/bending of the observed correlations between NSC and host-galaxy properties is a consequence of the nuclear mass erosion caused by MBH binaries. Finally, the lower panels of Figure 1 show the relations between \( M_{\text{CMO}} \) and galaxy properties in the NSC erosion model for nucleated galaxies with an MBH. Clearly, the choice of plotting the total \( M_{\text{CMO}} \) mass significantly reduces the broadening that characterized the \( M_{\text{NSC}} \) relations (upper panels), but the scatter is slightly larger than in the “NSC preservation” model (middle panels). This is expected since \( M_{\text{ej}} \) only equals the final MBH mass to first approximation (see Equation (1)).

The ancestry of an NSC includes complicated processes leading to its growth, disruption, and regeneration if new material is accreted after a disruptive merger. In Figure 2, we illustrate the typical evolution of NSCs as predicted by our fiducial “NSC erosion” model. Since the effect of MBH binaries and mergers on NSCs is most important for large galaxies (where they cause the broadening/bending of the correlations between NSC and host-galaxy properties), we choose a galaxy with a spheroid mass of \( \approx 2 \times 10^{10} M_{\odot} \), at which the NSC erosion becomes significant. In this example, the MBH grows by short-lived accretion events triggered by bar instabilities of the host’s galactic disk (at \( z \approx 6−7 \)) or by major galactic mergers (at \( z \approx 1−3 \); note the corresponding growth of the reservoir following the merger-driven infall of cold gas to the nuclear regions). The NSC grows more gradually through a combination of in situ star formation (especially at \( z \approx 1−3 \), when the growth of the reservoir triggers nuclear star formation) and infall of stellar clusters. The latter channel dominates over the former at high redshift and is also enhanced at \( z \approx 1−3 \) since major galaxy mergers also cause violent bursts of star formation, which in turn enhance stellar-cluster formation. Finally, at \( z \leq 1−2 \), the NSC gets eroded by a series of minor MBH mergers, but re-forms as a result of a steady infall of stellar clusters, which form as a result of quiescent star formation activity as the galactic disk regrows.

Figure 3 shows the redshift evolution of the \( M–\sigma \) relations for both MBHs and NSCs in the “NSC erosion” model (left panels) and in the “NSC preservation” model (right panels). In both models, the MBH growth appears inefficient at high redshifts relative to NSC growth. At redshift \( z \leq 2 \), after the epoch of bright quasars, MBHs become the dominant nuclear component in the most massive galaxies. Therefore, it is only at relatively late cosmic epochs that MBH mergers become efficient at scouring their host clusters in the “NSC erosion” model. As can be seen, the “NSC preservation” model clearly overpredicts the mass of NSCs in the brightest nucleated spheroids, while the “NSC erosion” model at \( z = 0 \) is in good agreement with the local \( M–\sigma \) relation for both MBHs and NSCs.

### 4. Conclusions

A comparison of our results to observational data reveals that the NSC scaling correlations in the local universe carry an imprint of the merger and growth history of their companion MBHs. NSCs are significantly eroded by MBH binaries, causing a broadening of the observed NSC empirical correlations in high-mass galaxies and at low redshifts.

The NSC scaling correlations can potentially be used to probe different NSC evolutionary models and also to place constraints on the merger and growth history of their host galaxies. However, the slope of the observed correlations involving NSC masses is lowered by the inclusion, at the high-\( \sigma \) end, of NSCs that were partly eroded by MBHs. Hence, such relations cannot be used to put reliable constraints on different NSC formation models without also taking into account the scouring effect of MBH binaries.

We argue that the stellar mass removed from the center during mergers is of the order of \( M_{\text{MBH}} \), and indeed we find that by replacing \( M_{\text{NSC}} \) with \( M_{\text{CMO}} = M_{\text{NSC}} + M_{\text{MBH}} \), the observed scaling correlations agree remarkably well with those predicted by models that do not account for the scouring effect of MBH binaries. Our findings provide a natural explanation to why relations between \( M_{\text{CMO}} \) and galaxy properties for nucleated galaxies show significantly less scatter than relations involving...
The relations between $M_{\text{CMO}}$ and galaxy properties are much shallower than the same correlations for MBHs. Our results also explain the well-known transition from MBH- to NSC-dominated galaxies as one proceeds from dwarfs to giant ellipticals, without the need of invoking competitive feedback processes from young NSC and/or AGN activity. Therefore, the formation of MBHs and NSCs appear not to be mutually exclusive, with NSCs being modified after their formation by the merger evolution of their companion MBHs.

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**Figure 3.** Redshift evolution of NSC and MBH $M-\sigma$ relations in our models with (left panels) and without (right panels) mass ejection due to MBH binaries. The bottom right panels compare our predictions to data. Blue open circles are NSCs; black open circles are MBH masses from Tremaine et al. (2002). Note the different evolution of the NSC mass vs. $\sigma$ relation in the two models at $z \lesssim 2$. Since reliable MBH mass measurements have been obtained almost exclusively for main early-type galaxies (e.g., Ferrarese & Ford 2005), in this analysis, we have neglected MBHs and NSCs in satellite galaxies and only included galaxies with bulge-to-total mass ratios of $B/T > 0.7$ in order to compare with the observed MBH $M-\sigma$ relation. However, if all galaxies were included, the NSC scaling correlations would be very similar to those shown here (see Figure 1, which was produced by considering all galaxies).
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