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The Co-evolution of Galaxies, Black Holes, and AGN in a Hierarchical Universe

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Abstract. The observational link between Supermassive Black Holes (SMBH) and galaxies at low redshift seems to be very tight, and statistically the global evolution of star formation activity and BH accretion activity also seem to trace each other closely. However, pinning down the co-evolution of galaxies and BH on an object-by-object basis remains elusive. I present results from new models for the joint evolution of galaxies, SMBH, and AGN, which may be able to help resolve some of the observational puzzles. A unique aspect of these models is our treatment of self-regulated BH growth based on hydrodynamic simulations of galaxy-galaxy mergers. Although these models do quite well at reproducing the observed evolution of galaxies, they do not reproduce the observed history of BH accretion, predicting too much early accretion and not enough at late times. I suggest two possible resolutions to this problem.

1. Introduction

There is strong evidence that the present-day properties of Supermassive Black Holes (SMBH) and their host galaxies are tightly linked — for example we observe a tight relationship between BH mass and the mass of the host spheroid in nearby galaxies (e.g. Häring & Rix 2004). However, we do not yet know whether this BH-galaxy mass relationship evolved over cosmic time, or how galaxies and SMBH arrived onto it. Perhaps most importantly, we do not yet understand the physical origin of this relationship.

Mergers have often been proposed as a mechanism that can drive gas into the nuclei of galaxies and fuel both starbursts and black hole accretion. Hopkins et al. (2005) used a large suite of hydrodynamic simulations of galaxy mergers to characterize the episode of black hole growth and the AGN accretion "lightcurves" in these events. Hopkins et al. (2006) then used this model to test whether observed galaxy merger rates, the build-up of red/spheroidal galaxies, and AGN luminosity functions are consistent with the picture in which mergers both trigger AGN activity and cause morphological and color transformation. They concluded that there is excellent statistical agreement between all of these quantities.

However, establishing a direct link between mergers and AGN activity has proven controversial. Low luminosity AGN, which are more common and can be studied in more detail at relatively low redshift ($z < 1$), do not show strong evidence for being predominantly in morphologically disturbed hosts or close pairs (e.g. Li et al. 2006; Pierce et al. 2007). Higher luminosity quasars seem to be more often (though not always) associated with disturbed hosts or to have close companions (Bahcall et al. 1997; Bennert et al. 2008; Letawe et al. 2008), but the samples with high resolution imaging are small. It may be the case that AGN are most easily identified in the very late stages of mergers, when the two nuclei have completely coalesced and most signs of morphological disturbance have become invisible. Especially at high redshift, at the typically available image sensitivity, these very late stage merger remnants might well appear to be "normal" spheroidal-type galaxies.

Of course it is also possible, even likely, that there are multiple modes of BH growth. There are ample suggestions in the literature that AGN activity could also be fed by bars or by stochastic accretion of cold gas in galactic nuclei. Hopkins & Hernquist (2006) presented a model for fueling of BH in isolated disks by stochastic accretion, and argued that while this fueling mode may be important in lower luminosity objects and at late times, most of the growth of today's massive BH occurred in the merger-driven mode at high redshift.

Another sign of co-evolution is that the global histories of star formation and BH accretion seem to trace each other remarkably closely over the whole range of lookback times over which these quantities have robust observational estimates. The global star formation rate density is almost exactly a factor of 2000 times the BH accretion rate density, from redshift $z \sim 5$ to the present. Moreover, even when divided by mass or accretion rate, "matched" populations of galaxies and black holes at $z < 1$ also trace one another's activity (Zheng et al. in prep). However, we know that at least at $z < 1$, the bulk of the star formation activity is associated with *isolated* disks, not mergers or spheroids (Bell et al. 2005). Therefore, it is also strange that these two kinds of activity trace each other, but do not seem to be occuring in the same types of objects (Zheng et al. in prep).

At higher redshift, there may be a larger mismatch between between the two kinds of activity. Faucher-Giguere et al. (2008) obtained constraints on the global star formation density at $2 < z < 4.2$ from the Lyman-α forest opacity in QSO spectra. They found that the hydrogen photoionization rate, and hence the star formation rate density, was remarkably flat over this redshift range, in contrast to the sharply peaked QSO luminosity density, which falls off sharply at $z > 2$. This may indicate that there is a time delay between SF activity and QSO activity, which is naturally explained in the merger picture (any galaxy with cold gas can form stars, but galaxies have to "wait" for a major merger before significant accretion onto the BH can occur).

One way to test this picture, in which mergers are responsible for triggering both AGN activity and morphological and spectrophotometric transformation of galaxies, is to build cosmological models that treat the growth of galaxies, black holes, and AGN self-consistently. In addition, many astronomers now believe that the energy released by accreting black holes may play a crucial role in regulating galaxy formation. Here we describe one such semi-analytic model for the joint formation of galaxies, black holes, and AGN, and present some predictions from these models.

2. Unified Models for Galaxies, Black Holes, and AGN

The foundations of our model, which pertain to the growth of structure in the dark matter component, and the formation of galaxies, are described in

Somerville & Primack (1999), Somerville et al. (2001), and subsequent works. Briefly, the models are implemented within dark matter halo "merger trees", and include approximate treatments for atomic cooling of gas, photoionization, the formation of angular momentum supported disks (including estimates of their sizes and circular velocities), star formation according to an empirical "Kennicutt" Law, supernova feedback, and chemical evolution. We have recently implemented new machinery within this framework to treat black hole growth and the associated AGN feedback. Our new models are fully described in Somerville et al. (2008, S08). Here we give a very brief synopsis of the most important new ingredients. The models presented here are for a "Concordance" ΛCDM cosmology with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, $H_0 = 70$ km/s/Mpc, $\sigma_8 = 0.9$, $n_s = 1$.

Galaxy-galaxy Mergers We assume that galaxy mergers may induce a burst of star formation and destroy any pre-existing disk component, depending on the mass ratio of the smaller to the larger galaxy, μ. We parameterize the strength and timescale of these bursts according to the results of a large suite of hydrodynamic simulations of galaxy mergers (Robertson et al. 2006b; Cox et al. 2008), as described in S08. Mergers can also heat and thicken, or even destroy, a pre-existing disk component, driving galaxies towards morphologically earlier Hubble types. We assume that the fraction of the pre-existing stars that is transferred from a disk to a spheroidal component is a strongly increasing function of the merger mass ratio μ, such that minor mergers with $\mu < 0.2$ have little effect, and major mergers with $\mu > 0.25$ leave behind a spheroid-dominated remnant.

Bright Mode AGN and AGN-driven winds In our model, mergers also trigger the accretion of gas onto supermassive black holes in galactic nuclei. Each top-level halo in our merger trees is seeded with a black hole of mass $M_{\rm seed} \simeq 100 M_\odot$. Following a merger, the black hole is allowed to grow at the Eddington rate until the BH reaches a critical mass, where the radiative energy being emitted by the AGN becomes sufficient to halt further accretion. This self-regulated treatment of black hole growth is based on hydrodynamic simulations including BH growth and feedback (Springel et al. 2005b; Di Matteo et al. 2005; Hopkins et al. 2007a), and is described in more detail in S08. Energy radiated by black holes during this "bright", quasar-like mode can also drive galactic-scale winds, clearing cold gas from the post-merger remnants (Springel et al. 2005a). Our model for momentum-driven AGN winds is described in S08.

Radio Mode Feedback In addition to the rapid growth of BH in the merger-fueled, radiatively efficient "bright mode" described above, we assume that BH also experience a low-Eddington-ratio, radiatively inefficient mode of growth associated with efficient production of radio jets that can heat gas in a quasi-hydrostatic hot halo. The accretion rate in this phase is modelled assuming Bondi accretion using the isothermal cooling flow solution of Nulsen & Fabian (2000). We then assume that the energy that effectively couples to and heats the hot gas is given by $L_{\rm heat} = \kappa_{\rm heat} \eta \dot{m}_{\rm radio} c^2$, where $\dot{m}_{\rm radio}$ is the accretion rate onto the BH, $\eta = 0.1$ is the assumed conversion efficiency of rest-mass into energy, and $\kappa_{\rm heat}$ is a free parameter of order unity.

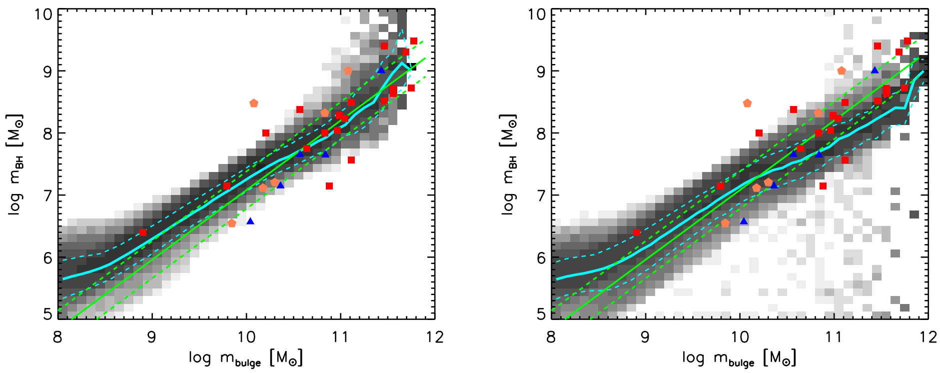

Figure 1. The predicted relationship between bulge mass and black hole mass (grey shading indicates the conditional probability $P(m_{\rm bh}|m_{\rm bulge})$; light blue solid and dashed line shows the median and 16th and 84th percentiles) compared with the observed relation from Häring & Rix (2004, green lines). Symbols show the measurements for individual galaxies from Häring & Rix (2004).

3. The Global Evolution of Galaxies and Black Holes

We normalize the free parameters in our models to reproduce a key set of observational quantities at $z \sim 0$, such as the stellar mass function, the cold gas fraction in disk galaxies, and the stellar metallicity (S08). We show our model predictions and compare with observations for a broad range of low redshift galaxy properties in S08.

The relationship between galaxy mass and BH mass is clearly a key result that our model should reproduce. In our model, this relationship is set by the depth of the potential well of the galaxy at the time when the BH forms, which in turn is determined by the gas fraction of the progenitor galaxies of the last merger. More gas-rich progenitors suffer more dissipation when they merge, and produce more compact remnants with deeper potential wells. A deeper potential well requires more energy, and therefore a more massive BH in order to halt further accretion and growth. We see from Fig. 1 that our fiducial model reproduces the observed slope and scatter of the $M_{\rm BH}$–$M_{\rm sph}$ (black hole mass vs. spheroid mass) relationship. Our model also predicts that the $M_{\rm BH}$–$M_{\rm sph}$ relation should evolve with time. Because more gas-rich merger progenitors produce remnants with larger black holes, and the galaxies in our models were significantly more gas rich in the past, galaxies have larger BH for their spheroid mass than they do at the present day. This leads to a relatively mild amount of evolution, of a factor of less than two since $z \sim 1$ and a factor of about four since $z \sim 3$ (Hopkins et al. 2007a).

Fig. 2 shows the global star formation rate density of all galaxies predicted by our models. We show both the results of our "fiducial" model, as well as a model in which galaxy formation has been suppressed in low-mass halos (we simply do not allow gas to cool in halos with mass less than $10^{11} M_\odot$). We will

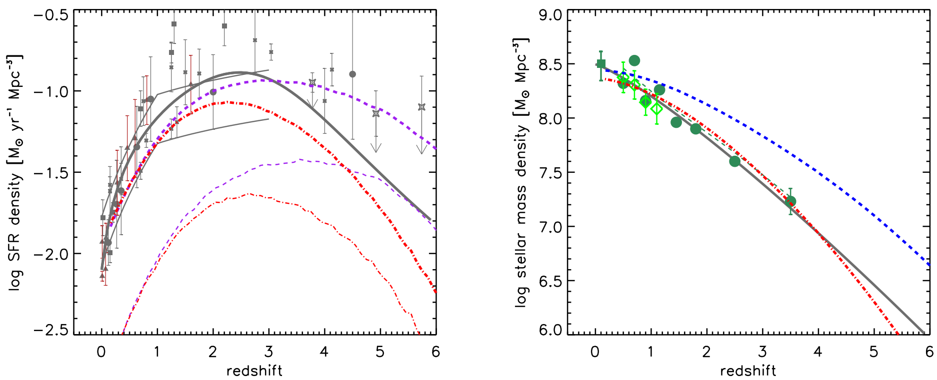

Figure 2. Left: Star formation rate density as a function of redshift. The upper set of thicker lines shows the total SFR in the models, and the lower set of thin lines shows the SFR due to bursts. Symbols and solid lines show a compilation of observational results, converted to a Chabrier IMF (see S08 for details). Right: The integrated global stellar mass density as a function of redshift. Symbols and the solid line show observational estimates (see S08). In both panels, dashed (purple) curves show our "fiducial" ΛCDM model, and dot-dashed (red) curves show a model with reduced galaxy formation in small mass halos (see text).

refer to the latter model as the "low" model for brevity. The results of the low model are similar to those from models with reduced small scale power, e.g. with lower σ_8. We have kept the same values for the free parameters in both models. Both models fit the data fairly well from $0 < z < 1$, and are about 0.15–0.2 dex lower than the observational compilation of Hopkins & Beacom (2006) from $1 < z < 3$. The fiducial model predicts much more star formation at very high redshift ($z > 3$) than the low model, because much of the star formation at these redshifts is taking place in low-mass halos.

In the right panel of Fig. 2 we show the complementary quantity $\rho_{\rm star}$, the integrated cosmic stellar mass density. The fiducial model predicts a significantly *earlier* assembly of stars in galaxies than observations of high redshift galaxies indicate. However, the low model produces very good agreement with the stellar mass density as a function of redshift. We note that this tension in the model results is connected with a possible inconsistency between the two observational data sets (star formation rates and stellar masses) that has been noted recently in several papers (e.g. Hopkins & Beacom 2006; Fardal et al. 2007; Wilkins et al. 2008; Davé 2008). One possible resolution of this tension can be obtained if the stellar IMF has changed with time, and was more top-heavy at high redshift.

4. Evolution of "Bright Mode" AGN

Fig. 3 shows the integrated bolometric luminosity density of "bright mode" BH accretion in our models, compared with observational estimates from quasar luminosity functions (Hopkins et al. 2007b). We see that in our fiducial model, QSO activity peaks at too high a redshift, and falls off too rapidly at low red-

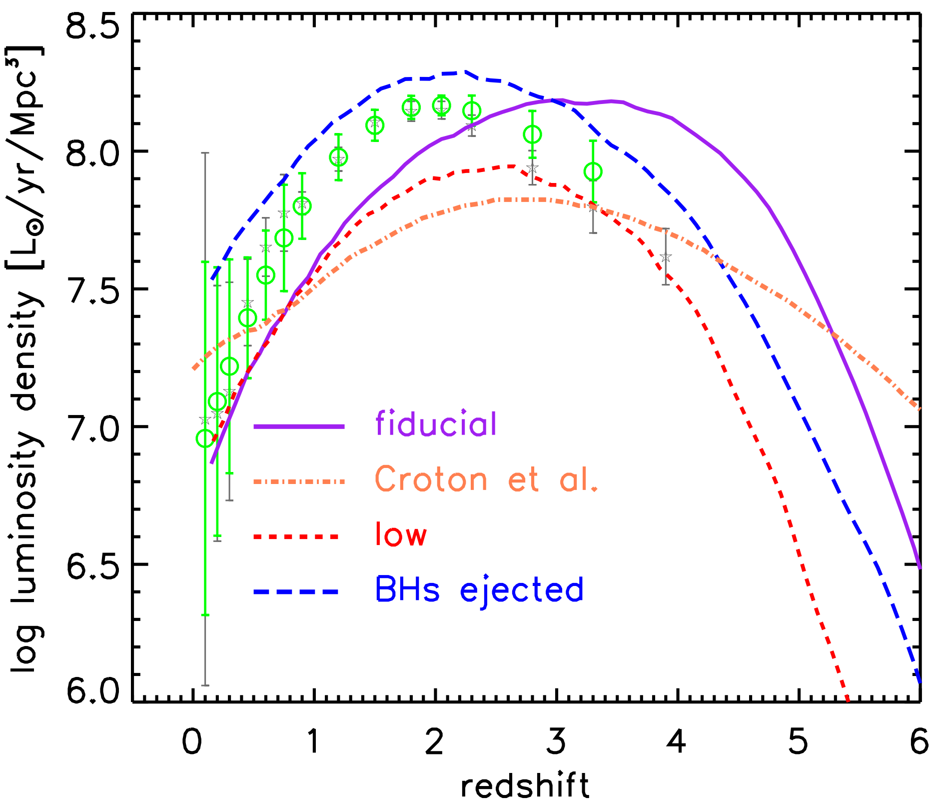

Figure 3. The bolometric luminosity density of "bright mode" AGN (quasars) as a function of redshift. Symbols with error bars show the observational estimates from Hopkins et al. (2007b). Lines show model predictions from: our fiducial model (solid), our "low" model (short-dashed), a model in which black holes are ejected after every merger (long dashed), and the model of Croton et al. (2006).

shift. The "low" model predicts a rise and fall in QSO activity that is in somewhat better agreement with the data, but still does not have quite the right shape. For comparison, we plot the bright mode accretion rate in the models of (Croton et al. 2006), which are similar to our fiducial models in many respects, but treat BH growth and AGN feeding differently. We see that this model also fails to reproduce the observations: QSO activity peaks too early, and does not fall off rapidly enough at low redshift.

This result is surprising, because Hopkins et al. (2008b) found good agreement with these same observations, using the same model for BH growth that we have implemented here. We checked that the merger mass function predicted by our model agrees with that in the Hopkins et al. models. The gas fractions of our merger progenitors also agree well. Eventually we realized that an important difference in the assumptions made by Hopkins et al. (2008b) and those contained in the models presented here was that, in the Hopkins et al. model, the black holes were allowed to grow from the seed mass to the final mass *in each merger*. This effectively neglected the pre-existing BH that grew in earlier mergers. Put another way, in our models, by $z \sim 1$–2, there is already a significant amount of mass in spheroids in place, each containing a massive black hole. If the pre-existing BH is already above the critical mass discussed above, then no AGN activity takes place. Thus, in our models, many late mergers do not trigger any AGN activity.

As a check, we re-ran our model, assuming that the black holes are ejected from the galaxy at the end of every merger. The bright mode accretion history now agrees much better with the observations at least in shape, although the normalization is a bit high. Although this model may seem artificial, it is possible that in some cases black holes are actually ejected by the gravitational rocket mechanism, which may impart kicks of several hundreds to 1000 km/s to merging BH (Volonteri 2007, and references therein). However, this ejection of massive BH can clearly have a problematic impact on the predicted $M_{\rm BH}$–$M_{\rm sph}$ relation, as shown in Fig. reffig:mbh. However, the model shown here is extreme in that BH are ejected from every galaxy after every merger. It is possible that a more physical implementation of the gravitational rocket mechanism could improve the BH accretion history without leaving behind too many massive spheroids with no BH, or with very low mass BH, which are not observed.

Another possible resolution to this problem could perhaps be obtained if spheroids are not formed as efficiently in high redshift major mergers as we have assumed here. Because in our models, the properties of the spheroid regulate BH formation, if spheroids form later, then BH accretion will occur later as well. There are indications from a detailed analysis of the hydrodynamic merger simulations that gas-rich mergers may often produce disk-like, rather than spheroidal, remnants (Robertson et al. 2006a; Hopkins et al. 2008a). Because our disks tend to be more gas rich at high redshift, this effect would indeed shift spheroid formation to later times. We are currently working on implementing this effect in our models.

5. Summary and Conclusions

We have presented some first predictions from new models for the joint evolution of galaxies, black holes, and AGN. Our models differ from other semi-analytic models in the literature in that we have implemented self-regulated BH growth based on the results of high resolution hydrodynamic simulations of galaxy mergers.

We showed that our fiducial model does a fairly good job of reproducing the global star formation history, but overproduces the stellar mass in place at high redshift. A "low" model with cooling suppressed in low-mass halos, or a model with reduced small-scale power, produces good agreement with the stellar mass density history but does not agree as well with the star formation history. This reflects an internal tension between these two data sets, which may be due to systematic errors arising from a time-varying stellar Initial Mass Function.

We found that our model, which does fairly well at reproducing galaxy observations at both low and high redshift, fails to reproduce the form of the BH accretion history as traced by the bolometric quasar luminosity density. In our models, QSO activity peaks at too high a redshift, and falls off too rapidly at low redshift. The models of Croton et al. (2006) also fail to reproduce this behavior. We suggested two possible resolutions to this problem: 1) Black Holes are (at least sometimes) ejected from their host galaxy following a merger or 2) major mergers at high redshift are not as efficient at producing spheroidal remnants as we have assumed.

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