Modeling AGN Feedback

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Abstract

Active Galactic Nuclei (AGN) are believed to be intricately involved with the evolution of their host galaxies through a process called AGN feedback. The mechanisms by which this occurs are not well-understood. It has been known for some time that the population of high-luminosity AGN, associated with large supermassive black holes, peaked during the early universe, and are extinct in the modern universe. AGN activity in the universe peaked around the same time as galactic star formation, and while this correlation is not completely understood, astronomers consider it a strong possibility that AGN play an important role in the regulation of star formation rates. Refining modeling methods will be more useful as observational resolution is increased by future telescope missions. AGN feedback may be responsible for quenching cold stellar winds, thus reducing star formation rates, and is needed to reproduce the observed intergalactic medium. Chaotic cold accretion is a likely mechanism by which AGN feedback occurs, allowing the AGN to "cycle" through a process of heating and cooling that reaches equilibrium with the host galaxy, until available cold gases are consumed. Modeling AGN feedback presents significant challenges, but has improved upon observational predictions derived from the ΛCDM cosmology-based Millennium Simulation. Only a few subclasses of AGN have been studied regarding their feedback mechanisms, and with only the most rudimentary first-principle approaches, but the necessity of including AGN feedback to correctly predict colors and luminosities of galaxy mergers and quasars seems increasingly likely. Two possible future models are also considered, one a more rigorous derivation involving chaotic cold accretion, and the other a "bubble" model of heated outflows.

1 Introduction

Quasars are the most luminous objects in the cosmos ($10^{12} - 10^{15}$ $L_\odot$. In 1964, Zeldovich and Novikov described for the first time the luminosity of a quasar emerging from the accretion of matter by a supermassive black hole (SMBH). [5] We now know that SMBHs on the order of 10^6 - 10^9 $M_\odot$ are common at the center of galaxies, and when their accretion process results in strong luminosities across the electromagnetic spectrum, we call these Active Galactic Nuclei (AGN). [3] [6] Gas is readily available in the central region, shed by stars during their evolution, and from tidal disruptions caused by the SMBH. Galactic mergers increase the amount of fuel available to the AGN, and may be responsible for the extreme luminosities seen in quasars, as the SMBH accretion rates increase in response. The Eddington luminosity L_E describes the luminosity necessary to induce radiation-driven outward matter flows, and for pure ionized hydrogen,

$$L_E = \frac{4\pi c G M m_p}{\sigma_T} \approx 1.3 \times 10^{38} \text{ergs s}^{-1} \frac{M}{M_\odot}. \tag{1}$$

Quasars are AGN radiating near or above their Eddington luminosities, making this an important measure of their brightness, and at $> 10^{45}$ergs s^{-1} they can outshine their entire host galaxy! For

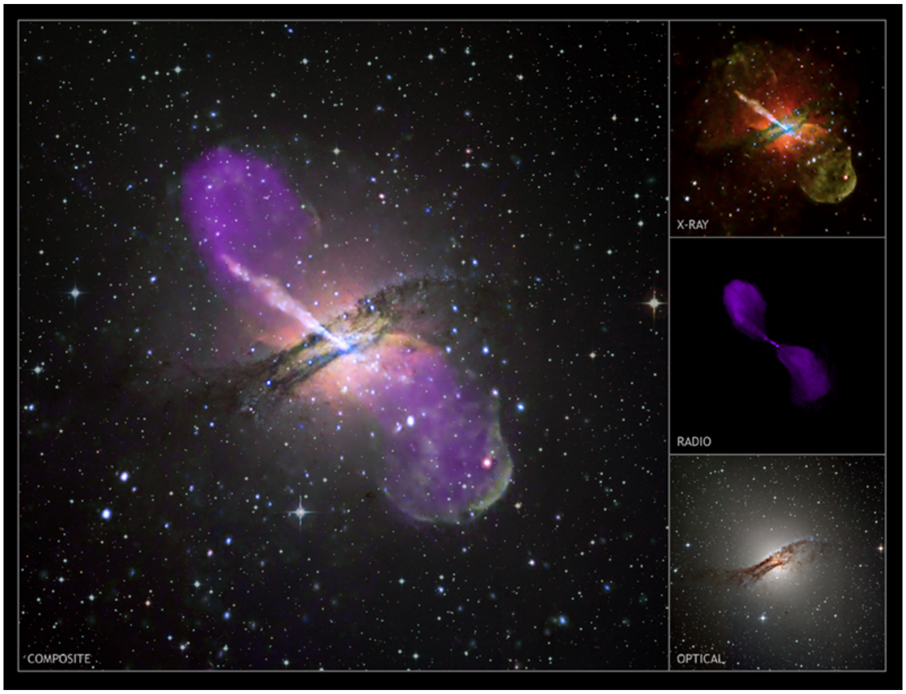

Figure 1: Centaurus A (NGC 5128), a nearby radio galaxy whose active galactic nucleus ejects a relativistic jet with discernible emission in X-ray and radio wavelengths. This galaxy has a supermassive black hole equivalent to 55 million $M_\odot$. A galaxy collision is suspected to be the cause of increased star formation and nuclear activity. [7]

a 10^9 $M_\odot$black hole to maintain its Eddington luminosity, it must accrete 40 $M_\odot$per year. Central black holes in present-day galaxies apparently accrete at medium-to-low rates compared to rates needed to produce L_E, and observational studies show that quasars were much more common in the past, with their activity having peaked about 10 Gyr ago. [6]

1.1 Cosmology

Cosmology will not be covered in this work, but it is important to define a few terms. Many models of galaxy formation begin with the ΛCDM cosmological structure predicted by the Millennium Run or other spatial structure simulation. ΛCDM cosmology is the "standard model" of cosmology that includes the cosmological constant Λ that defines the rate of expansion of the universe and cold dark matter (CDM), which is gravitationally significant but otherwise non-interacting and non-colliding. The Millennium Run and its following iterations are N-body simulations that predict the evolution of the spatial distribution of matter in the universe. It is considered a (successful) test of the ΛCDM cosmology because it strongly coincides with the observed structure of the cosmos, and data from the iterations of the run are stored such that models can be built on top of them to predict observational quantities as needed. The density of a region is characterized by its halo mass, a measure of the mass distribution of dark matter halos, and therefore of the overall matter density in a region. [11]

Also, some astronomical epochs are measured in their redshift z in this work. One only need be aware that because the speed of light is constant in a vacuum, and because the universe is expanding at an accelerator rate, combined with the principle of Doppler shift, a redshift corresponds to a distance and a historical time at which an object was observed. Greater redshifts correspond to objects that are more distant across space and farther back in time.

A note of Caution

AGN are energetically capable of regulating star formation through a number of suggested processes, but it is uncertain what caused the observed attenuation of star formation and what role AGN played in it. The timescales of feeding and feedback mechanisms are also uncertain. Great care must be taken when interpreting new data, as the AGN and stellar formation relationship may have phases, or may not exist at all. [3]

2 AGN May Regulate Galaxy Evolution

For some time, astronomers have been aware that AGN and host galaxy evolution are correlated. The strong coupling of black hole mass with velocity dispersion in the surrounding galactic bulge was one of the first hints at this relationship, going back to 1998. [5] [13] In most massive galaxies, galaxy formation models require the injection of momentum by an AGN into the surrounding gases in order to reproduce the low rate of cooling observed in galaxy clusters and the inefficiency of star formation in massive galaxy halos. It is widely believed that the electromagnetic radiation from AGN regulates the rate of star formation in the host galaxy. Stellar feedback processes, such as supernovae, are also present but do not fully account for observations. Figure 2 demonstrates the necessity of including AGN feedback to predict stellar mass-halo mass ratios. The method for modeling AGN feedback is rudimentary, involving only a direct transfer of momentum from the AGN to the out-lying gas, so that it can account for this discrepancy is remarkable. [3] Furthermore, the high-mass end of the galaxy stellar mass function is over-predicted by modern simulations, indicating a phenomenon to regulate stellar formation is necessary, and AGN feedback is a strong candidate to fill this role. [13]

The mechanisms used by AGN feedback are under debate, and the discovery process is still disparate. X-ray astronomy has detected signatures from powerful disk winds in quasars, which are believed responsible for feedback effects during high-luminosity modes of the AGN. These winds have been observed close to the accretion disk, but are likely to have strong effects over galactic-scale distances. A connection has also been observed between one of these powerful accretion disk winds and a molecular outflow with infrared emission in a nearby galaxy, IRAS F11119+3257. This object is likely the result of a merger between two galaxies; mergers are an expected common mode of igniting Eddington luminous quasars, and are discussed in Section 3. It is expected that improved resolution from future X-ray observatories, specifically ASTRO-H and Athena, will give a better picture of these outflows. [13]

Radio galaxies are an important sub-class of galaxy associated with AGN, and at least some show environmental and host properties that are consistent with gradual fueling via gas accretion onto a SMBH. [12] All elliptical galaxies are of interest in this field, in fact. Observations reveal regularities in these structures not predicted by the physics in current models. Initial conditions and the growth of CDM structure correctly predict the absorption by intergalactic medium density fluctuations, suggesting that the missing physics may lie with the baryons. [4] As noted earlier, black hole mass of the central SMBH and velocity dispersion in the bulge of a galaxy are strongly correlated. Bulges are understood to result from galactic mergers of 2 or more massive galaxies, and these mergers have become a primary galactic evolutionary process used in the attempt to model AGN feedback.

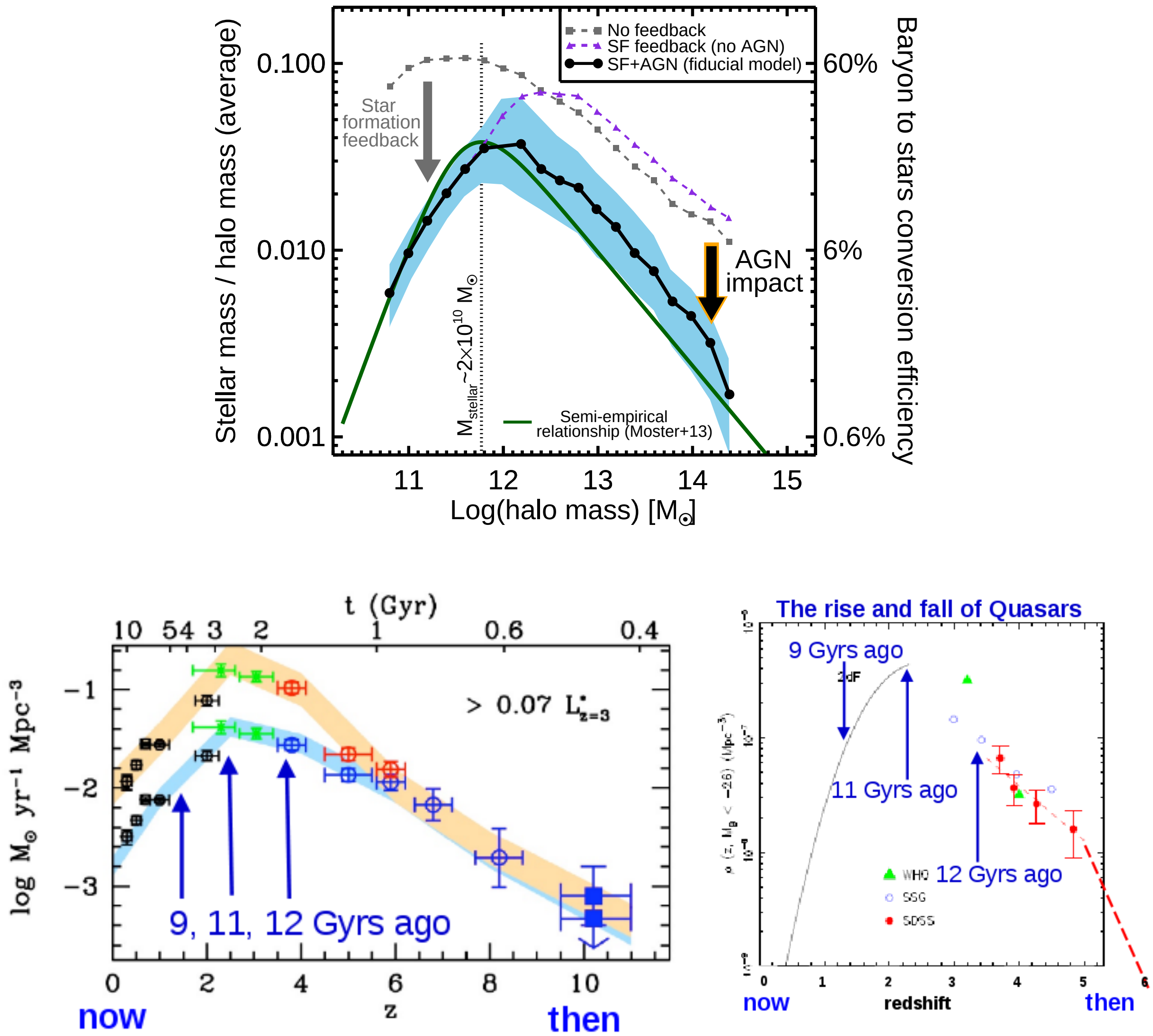

Figure 2: Above: AGN feedback is necessary to predict stellar mass-halo mass ratios. Stellar formation feedback helps reproduce the proper ratios at low halo masses, but does not sufficiently account for the regulation of stellar formation at high halo masses. [3] Below Left: Star formation rate as a function of redshift z, i.e., age of universe. Bottom Right: Quasar density as a function of the same. Star formation and quasar density both peak about 11 Gyrs ago. [5]

3 Modeling AGN Feedback in Galactic Mergers

Elliptical bulges are a characteristic feature of galaxies having undergone a merger. The ΛCDM cosmology predicts ubiquitous mergers, so bulge formation occurs easily in these simulations. Semi-analytic methods (SAMs) are a set of analytic models that are applied on top of the dark matter halos predicted by a simulation, such as the Millennium Run. SAMs lump all bulges under the label "spheroid", then allow a disk to form around the spheroid from subsequent accretion of gas; all mergers above a given mass ratio result in spheroids. The galaxy morphology is defined by the spheroid to disk mass ratio. This approach reproduces the relationship between morphological type and color, color-magnitude relation, and observed populations of galaxy morphologies. SAMs also reproduces the number density of spheroids for high-luminosity galaxies, but over-predicts the number density among low-luminosity galaxies, and does not distinguish pseudobulges at all. There are several possibilities for this error: it may be introduced when computing the halo merger rates to stellar galaxy mergers; pseudobulges might be covering up already-existing bulges; mergers can result in pseudobulges; or classical bulge formation may be less efficient than currently thought. [1]

Historical simulations have produced galaxies with mass overly-concentrated at the center and with over-large bulges. This is a result of "overcooling". [1] [13] [12] Baryons cool rapidly, resulting in dense concentrations of stars and gas. The galaxies undergo multiple mergers, and each time the baryons transfer orbital angular momentum to the dark matter of the accreting halo. The dense baryons arrive at the center of the halo with almost no angular momentum, resulting in the classic sign of the "angular momentum catastrophe". Stellar feedback is a promising avenue to solve the cooling problem but takes places on a scale much too small to be resolved in cosmological simulations, so only global trends can be modeled. Current observational resolution presents the same issue. Stellar feedback is also not sufficient to reproduce small bulges in Milky Way-like massive disk galaxies, so this model either needs to be improved or AGN feedback is needed. [1]

3.1 Chaotic Cold Accretion

AGN feedback may be responsible for quenching the cooling winds from the "cooling problem". Figure 3 shows one hypothesized cycle over which AGN feedback occurs, and the flow of fueling gases that feed the AGN and stellar populations. This is known as Chaotic Cold Accretion (CCA), and is perhaps the most accepted hypothesis for an AGN feedback paradigm. A gas reservoir with fuel for black hole accretion must be available, and this fuel is shared between the SMBH growth and star formation. Often the considered case is after a merger, when a large amount of free gas is available near the core. The turbulent, heated atmosphere and cold clouds surrounding the AGN condense to rain kpc-scale filaments onto the SMBH. Chaotic mixing of the inward flow boosts the accretion rate by a factor of up to 100. AGN outflows pick up, quenching cooling flows and star formation, but without destroying the core. A heated halo grows around the SMBH until it stifles the forming of multiphase gas and accretion, allowing it to cool. Once the halo cools, accretion resumes, and the cycle repeats. An equilibrial, symbiotic link can be reached between the SMBH and the whole host galaxy via this self-regulated feedback. [2]

3.2 Quasar Activation by a Merger

As part of this process, we expect a quasar to reach its peak luminosity as the accretion rates increase from the additional fuel supplied during a merger. Figure 4 shows a possible timeline for this to occur.

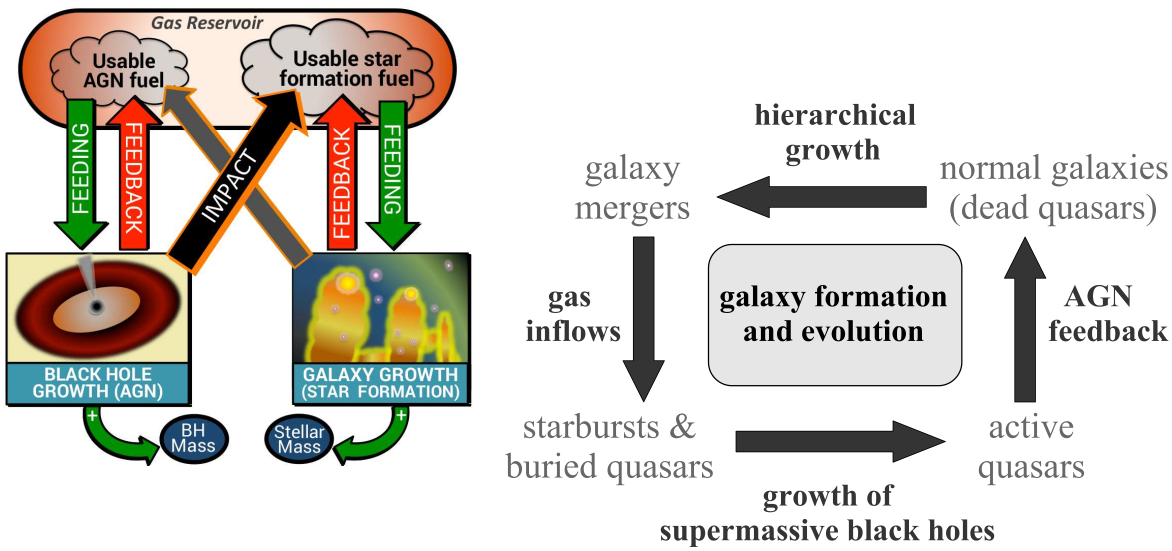

Figure 3: Left: Schematic illustrating the fuel supply relationship between galaxy and black hole growth. Gas in the reservoir is replenished during a galaxy merger, from interstellar material, or recycled internal galactic material. AGN fuel must lose sufficient angular momentum to fall deep into the gravitational well. Both processes reduce the availability of fuel by ionizing, heating, shocking, and expelling material, but they can have both positive and negative impacts on fuel availability for the other process. [3] Right: Schematic of the "cosmic cycle" that plays out between galaxy formation and evolution regulated by black hole growth in galaxy mergers. Galaxies in the modern universe typically contain dead quasars. Mergers and other sources of inward gas flows trigger black hole growth through accretion, leading to strong luminosities, which lead to AGN feedback and the possible continuation of the cycle at each iteration. [4]

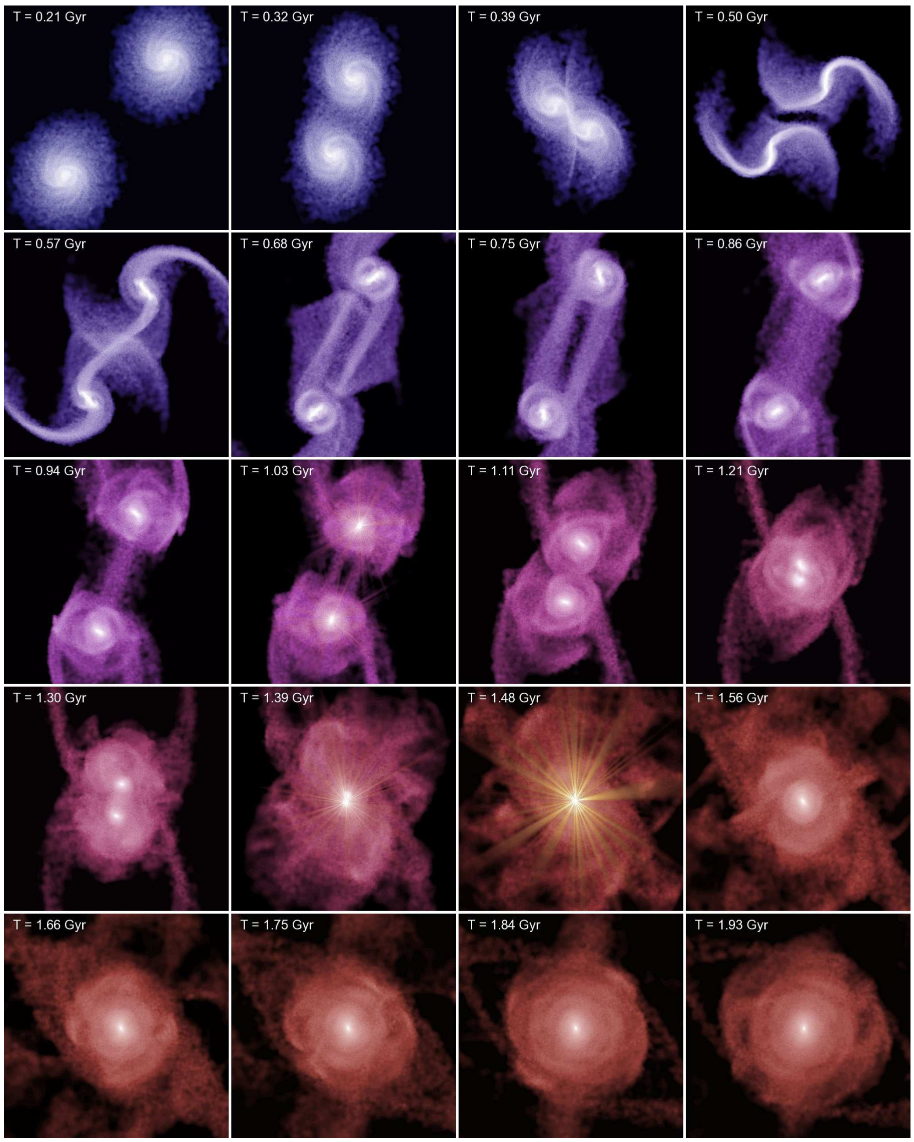

Figure 4: Time-sequence simulation of a merger resulting in quasar activation. The optical quasar mode can be seen at T=1.03,1.39, and 1.48 Gyr. This behaviour is expected as new gas becomes available as fuel for the SMBH during and after the merger. This process is in turn expected to lead to increased AGN feedback, heating surrounding gases and attenuating star formation rate.

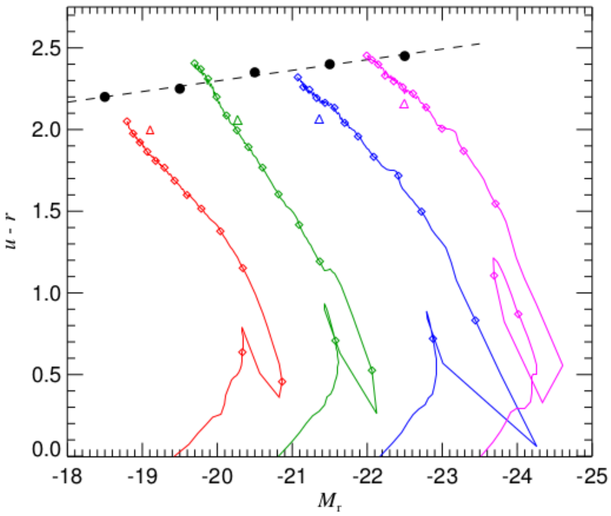

Figure 5: Bimodal color evolution for gas-rich mergers with black hole accretion. Symbols on the tracks are spaced 0. 5 Gyr apart, with the last point corresponding to an age of 5. 5 Gyr after the merger-induced starburst. Triangles show mergers without black holes at the same time, and the solid circles give the observed mean color of the red part of the bimodal color distribution at a given luminosity. [9]

3.3 Momentum Transfer Techniques

One of the most extensive attempts to model AGN feedback was carried out by Springel et al., who are involved with the Millennium Run as well as semi-analytic methods for predicting observables from the Millennium Run data. Their most up-to-date model involves two SMBH modes: a quasar mode and a radio mode. In either case, their feedback mechanism simply transfers and conserves momentum from the AGN to the out-lying gases, with no consideration given to the mechanism of transfer. [11] Considering numerical simulations do not currently include resolution sufficient to resolve transfer mechanisms within the SMBH system, this approach is not unreasonable, and we refer to it as an "effective subresolution model". [10] Even in its limited form, this approach has allowed proper modeling of some phenomena. In addition to predicting star formation rates accurately, the Springel et al. model also hints at further AGN feedback dependence in the predicted bimodal color distribution, seen in Figure 5. Without AGN feedback, the galaxy models do not reach their final color within the observed time. [9]

4 Toward a better Model

Observational resolution is increasing quickly, and computational resolution will need to keep up. We are at the threshold of reaching the resolution needed to differentiate between possible AGN feedback mechanisms. Attempts are underway to define a more rigorous model for AGN feedback. One approach attempts to unifying the micro and macro states using the CCA model discussed in Section 3.1 and derives a relationship using the mechanical efficiency

$$\epsilon = P/(\dot{M}c^2). \tag{2}$$

The large-scale outflow can then be modeled as

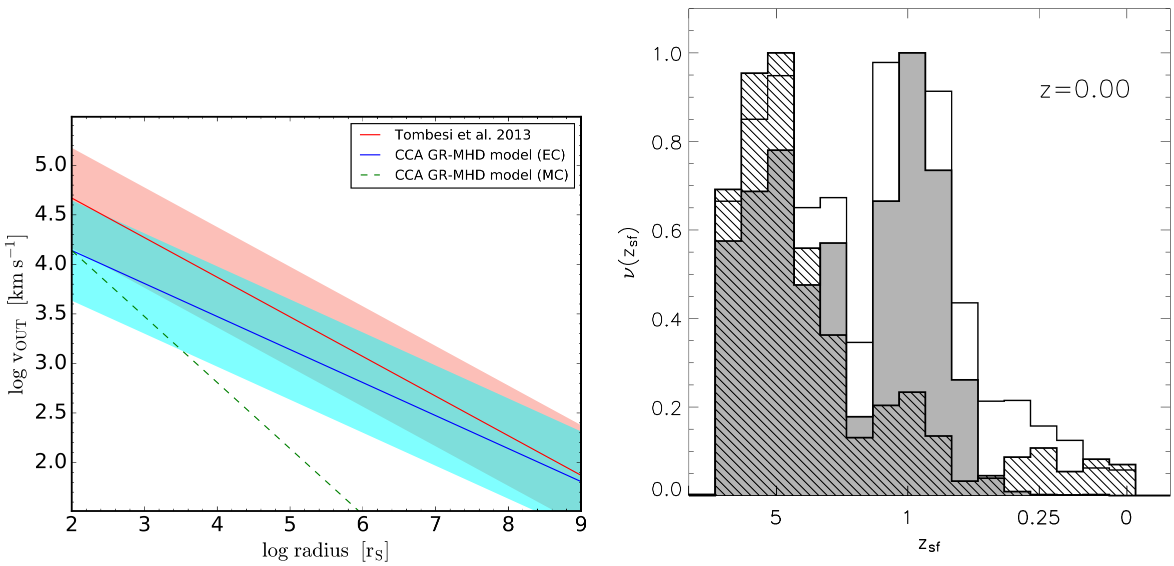

Figure 6: Left: Outflow velocity as a function of radial distance from the SMBH. The green dotted line shows the purely momentum-driven effective subresolution model. The red line is the velocity for the unified X-ray UFO plus warm absorber data reported by Tombesi et al. (2013). The shaded regions are UFO generated regions where most of the inflow mass is ejected. At larger radii, UFO entrains more mass, slowing down. This new model agrees more strongly with the UFO observations than the effective subresolution model. Right: Formation redshifts of the stars belonging to a model galaxy. The white histogram has only cooling and star formation, and it can be seen that star formation continues until the end of the simulation, which conflicts with observations. The grey and hatched histograms show how stellar formation times change when "bubble" heating is switched on, under two different models of this heating developed by Springel et al. This heating suppresses any central star formation for z < 0.25 completely, and in both cases suppresses the star formation enough to not be discounted as future hypotheses. [8]

$$P_{OUT} = \epsilon_{BH} \dot{M}_{cool} c^2. \tag{3}$$

An effective quenched cooling is derived such that it can be computed as

$$\dot{M}_{cool} \approx 6.7 \times 10^{-3} \frac{L}{c^2}, \tag{4}$$

where L_x is the luminosity escaping the AGN and c the adiabatic sound speed of the outflowing gas. A number of complications enter into this model, especially with entrainment of gases as outflows leave the AGN. The out-flow velocity can be derived as a function of this entrainment and compared to observations, seen in Figure 6. This model agrees with the UFO observations better than the effective subresolution model, and by a significant amount.

Another approach is to treat AGN feedback as the periodic release of heating "bubbles". Figure 7 demonstrates the concept. In this model, luminous winds drive the creation of pockets of hot gases that are blown into the regions surrounding the SMBH. This method has not been examined yet against empirical data, but at least Figure 6 indicates that the model does regulate star formation rates as expected. [8]

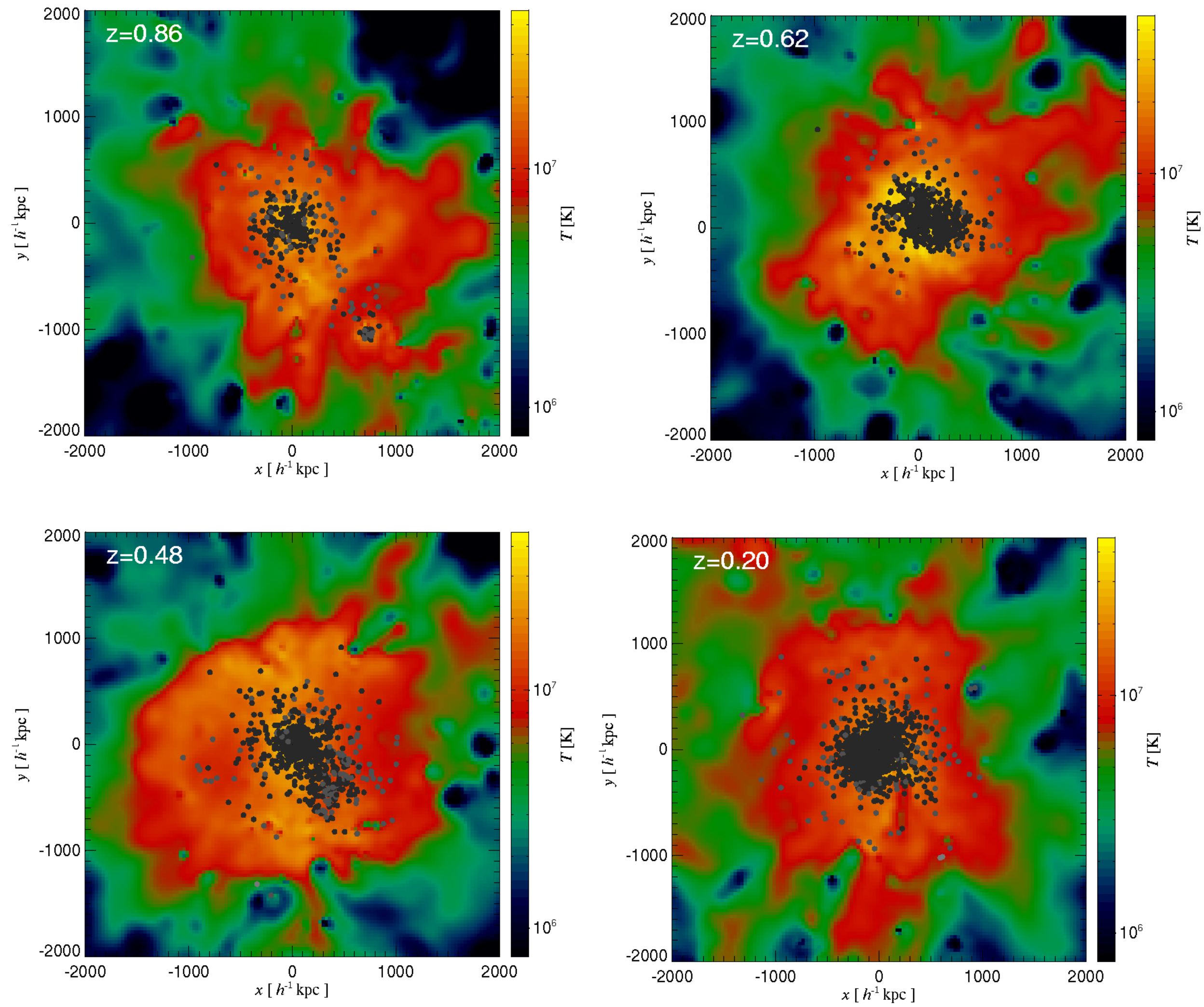

Figure 7: Emission-weighted temperature maps of a galaxy simulation involving AGN heating by non-uniform gases ("bubbles") after a major merger event, at several red shift epochs. [8]

5 Discussion

While it's not certain that AGN feedback is necessary to explain observed phenomena, especially the "overcooling program" and "angular momentum catastrophe", evidence strongly suggests that AGN feedback is a reasonable explanation to explore as the underlying regulator of these processes. Observation and computation resolution is too weak to properly differentiate between possible models of AGN feedback. CCA looks like a good candidate, but the "bubble" heat flow may also explain AGN feedback. The CCA unification model agrees with the small amount of comparable empirical data available, and this is a good sign. Until the "bubble" model is tested against empirical data, it should not be discounted either. Surely, there is much room for theorists to invent new models that attempt to explain AGN feedback, and perhaps something new will push this field forward. With new resolution, both observational and computation, around the corner, we shouldn't have to wait long to find out.

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