

Impact of supermassive black hole growth on star formation

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Abstract

Supermassive black holes are found at the centre of massive galaxies. During the growth of these black holes they light up to become visible as active galactic nuclei (AGN) and release extraordinary amounts of energy across the electromagnetic spectrum. This energy is widely believed to regulate the rate of star formation in the black holes' host galaxies via so-called "AGN feedback". However, the details of how and when this occurs remains uncertain from both an observational and theoretical perspective. I review some of the observational results and discuss possible observational signatures of the impact of super-massive black hole growth on star formation.

Introduction

The discovery that all massive galaxies host a central super-massive black hole rates among the most momentous in modern astronomy. These black holes, with masses ranging from hundreds of thousands to billions of times that of our Sun ($\approx 10^5$ – $10^{10} M_{\odot}$), primarily grow through periods of radiatively-efficient accretion of gas when they consequently become visible as AGN[1, 2]. Historically AGN were considered rare but fascinating objects to study in their own right, yet over the last two decades these phenomena have moved to the fore-front of galaxy evolution research. This is partly due to a number of remarkable observations that show that black hole masses are tightly correlated with host-galaxy properties, despite a difference of several orders of magnitude in physical size scales[3]. However, arguably the most influential factor in the explosion of interest in AGN are the results from galaxy evolution models.

Most galaxy formation models require AGN to inject energy or momentum into the surrounding gas (see Box 1) in the most massive galaxies (i.e., with stellar masses $M_{\text{stellar}} \gtrsim 10^{10} M_{\odot}$) in order to reproduce many key observables of galaxy populations and intergalactic material[4, 5, 6, 7, 8, 9, 10, 11, 12] (Fig. 1). These observables include: the "steep" relationship between X-ray luminosity and X-ray temperature observed for the gas in the intra-cluster medium within groups and clusters[13]; the "low" rate of gas cooling in galaxy clusters[14]; the inefficiency of star formation in the most massive galaxy haloes[15] (Fig. 1); the tight relationships between black hole masses and galaxy bulge properties[3] and the formation of quiescent bulge-dominated massive "red" galaxies that are no longer forming stars at significant levels[16].

AGN are an attractive solution in models to supply the

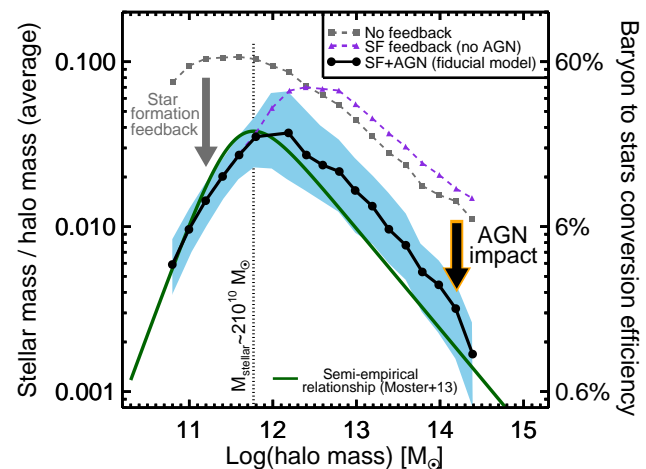
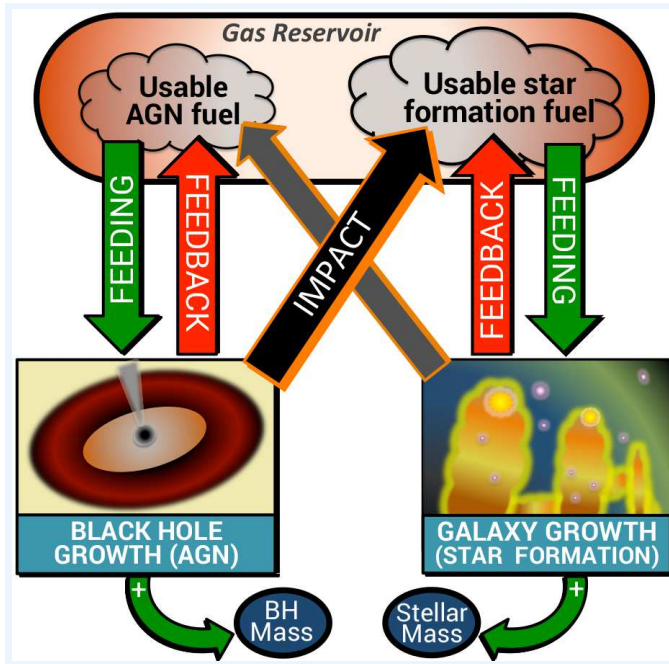


Figure 1 | The ratio of stellar mass to halo mass as a function of halo mass for three different runs of a simulation[6] and for the semi-empirical relationship[17]. The shaded region shows the 16th and 84th percentiles of the fiducial model that includes energy injection from AGN and star formation (SF). The right y-axis shows the efficiency for turning baryons into stars ($M_{\text{stellar}}/[f_b * M_{\text{halo}}]$; where the factor of $f_b = 0.17$ is the cosmological baryon fraction). The impact of including star formation feedback in the model is to reduce the efficiency of converting baryons into stars in low mass haloes. For massive haloes, energy injection from AGN is required in order to reduce these efficiencies. Such effects are required in most models in order to reproduce many observable properties of the massive galaxy population.



Box 1 | A schematic diagram to illustrate the relationships between fuel supply, galaxy growth and black hole growth.

Both AGN and star formation are fuelled by cold gas that originates from a shared (potentially hot) *gas reservoir* inside the galaxy halo. This gas reservoir can be fed by gas-rich mergers, by recycled material from internal galactic processes and by accretion of gas from intergalactic material. The amount of gas and the ability for this gas to cool determines the amount of usable fuel that can be used for *feeding* black hole growth and star formation. In the case of providing the fuel for black hole growth the material has the additional challenge of losing sufficient angular momentum to reach the inner sub-parsec region of the galaxy. Both processes are known to inject energy and momentum (via radiation, winds and jets) that can reduce the availability of usable fuel through ionising, heating, shocking or expelling material, and hence provide self-regulatory *feedback* mechanisms. A key component of most galaxy formation models is that these two processes can also have a positive or negative *impact* on the usable fuel supply for the other process (black and grey arrows). The focus of this article is observational results on the impact of black hole growth on star formation.

energy required to explain the observations. By releasing $\approx 10\%$ of the rest-mass energy of accreted material, they are phenomenal energy sources[18, 2]. For example, during the formation of a $\approx 10^8 M_{\odot}$ black hole $\approx 10^{54}$ Joules of energy is released, which is two-to-three orders of magnitude more energy than the binding energy of a typical host galactic bulge and is comparable to the thermal energy of the gas in the galaxy halo. Consequently, if only a small fraction of this energy is able to couple to the gas it will be capable of regulating black hole growth and the star formation in the host galaxy (see Box 1).

Whilst it is theoretically attractive to invoke AGN as a mechanism to regulate the rate of star formation in massive galaxies, this can only be credible if backed up by observational evidence. The observational task is to assess if and how accretion energy couples to gas and what resulting impact this then has on star formation in the AGN host galaxies.

Methods of energy injection by AGN

The energy released by black hole accretion (AGN) may be radiative (i.e., energetic photons) or mechanical (i.e., energetic particles)[19, 7, 20]. In models, radiative energy injection is sometimes called “quasar” or “wind” mode and is usually associated with high Eddington ratios ($\gtrsim 0.01$; i.e., mass accretion rates that are $\gtrsim 1\%$ of the theoretical maximum “Eddington limit”). In contrast mechanical energy injection is sometimes called “radio” or “jet” mode and is associated with low Eddington ratios. Early analytical models invoked galaxy-wide gas outflows, initially launched by accretion radiation coupling to the gas on small scales, to explain the observed scaling relationships

between galaxies and black holes[21, 22]. In hydrodynamical simulations energy injection from AGN is often crudely implemented; for example, by assuming a small fraction of the total radiative luminosity of accreting black holes couples thermally to the surrounding gas, with the result of expelling material from the host galaxy in an outflow and suppressing star formation[23, 24]. However, recently simulations have incorporated more complex prescriptions for “feedback” by invoking and testing multiple modes of energy injection[7, 25, 20]. Observational constraints on the different feedback prescriptions are a critical test of these models.

Based on the above, it is convenient to classify observed AGN into two broad categories: those for which their energetic output is predominantly radiative (radiative AGN) and those for which it is predominantly mechanical (mechanically-dominated AGN)[26]. Radiative AGN are luminous in X-rays, optical and/or infrared emission (sometimes also in radio emission) and are rare among the galaxy population as a whole (\lesssim a few percent)[27]. Mechanically-dominated AGN are usually identified through luminous radio emission[28]; however, those identified are found in the most massive systems and a rare subset of all galaxies which host low black hole accretion rates[26].

Mechanically-dominated AGN are pre-dominantly found in the most massive galaxies ($M_{\text{stellar}} \gtrsim 10^{11} M_{\odot}$) with old stellar populations, at least in the local Universe, whilst radiative AGN are most common in galaxies with on-going star-formation and younger stellar populations at all cosmic epochs[29, 28, 30]. Consequently, these two categories of AGN may represent distinct evolutionary phases and/or distinct black hole accretion mechanisms depending

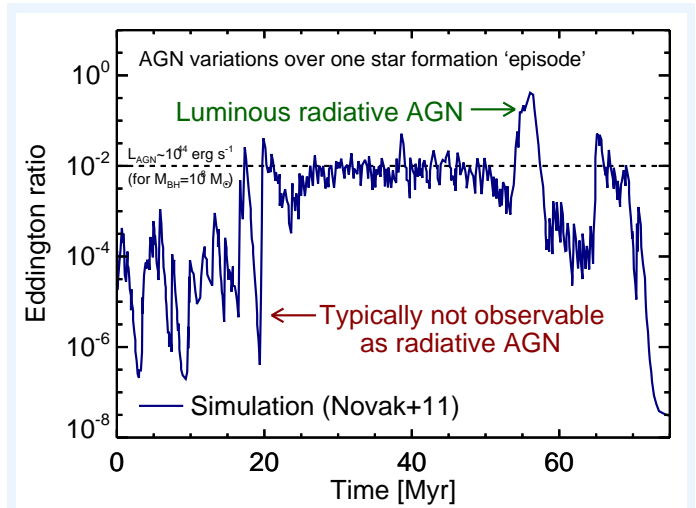
on the host galaxy mass and environment[31, 26]. Therefore, when assessing the impact of AGN on star formation it is important to consider these AGN types separately. Care is especially required for AGN that are identified through luminous radio emission that are increasingly more mechanically dominated towards later cosmic times (i.e., redshifts $z \lesssim 1$) and are increasingly more radiatively dominated at early cosmic times[32, 33].

Although the details remain uncertain there is compelling observational evidence, at least in the local Universe and in the densest environments, that radio jets driven by mechanically-dominated AGN can maintain host galaxy star formation at low levels. This is achieved by suppressing the ability for hot gas to cool (see Box 1) and has been reviewed extensively in the literature[19, 34, 35]. However, it is not yet fully understood what role AGN play in less dense environments[19, 36] or if gas needs to be ejected during earlier AGN episodes for these mechanically-dominated AGN to be effective at regulating gas cooling[37]. Furthermore, for these massive galaxies most of the galaxy and black hole growth occurred at earlier cosmic epochs than where this radio jet heating has been identified[38, 39] and it is not yet clear what quenched the earlier high rates of star formation in these systems[40].

To work towards addressing the outstanding issues raised above and to fully characterise the impact of AGN on star formation it is crucial to study and understand the role of *radiative* AGN. This is particularly true at early cosmic times (i.e., $z \gtrsim 0.5$), when significant levels of black hole and galaxy growth were occurring. The remainder of this review will focus on the observational evidence for the impact of radiative AGN on star formation. As described in Box 2 a common theme throughout the following sections will be awareness of the relative and uncertain timescales of: (1) visible AGN episodes; (2) star formation episodes and; (3) the impact of AGN energy injection on star formation.

Observing the mechanism of energy injection by radiative AGN

A common approach towards understanding the impact of AGN on star formation is to search for and to characterise a mechanism by which AGN are injecting energy and/or momentum into the gas in their host galaxies (see Box 1). For example, outflows may remove gas from the host galaxy and have the effect of suppressing star formation. Alternatively, AGN might kinematically disturb, compress, shock and/or heat the gas via outflows or jets and consequently reduce or enhance the ability for the gas to form stars. It is not the purpose of this review to comprehensively cover the huge amount of observational work on outflows or jets driven by radiative AGN (see [41, 42, 35, 12]). However, below I focus on some of the observational work that specifically investigates the impact that these outflows may have on star formation.



Box 2 | Eddington ratio versus times for an example simulation of an AGN to illustrate variability.

As discussed in detail in [98] various observational work indicates that AGN luminosities (L_{AGN}), in particular those derived from optical and/or X-ray continuum measurements that trace effectively *instantaneous* mass accretion rates, vary on orders of magnitude on timescales much shorter than the typical timescale of star formation episodes ($\gtrsim 100$ Myrs). Similar results are reached by AGN simulations; for example, the figure presents the results of the Eddington Ratio (proportional to the mass accretion rate and AGN luminosity) as a function of time for an example hydrodynamical simulation[99]. This model predicts that accretion rates can vary by several orders of magnitude on timescales of $\lesssim 1$ Myr. Consequently, measured AGN luminosities may provide little information on the cumulative energy released over the relevant timescales for star formation. Understanding the timescales traced by the various AGN luminosity indicators is crucial for our interpretation of the impact of AGN determined from observations. Furthermore, the relative timescales of a visible luminous AGN and the time taken for any resulting impact on the observed star-formation rates are very uncertain. Crucially, even when the AGN is responsible for enhancing or decreasing the star-formation rate in the host galaxy, it is most likely that the AGN luminosity will vary much more rapidly than the star-formation rates[100, 94]. Such effects are important to consider when assessing the impact of AGN on star formation through observations.

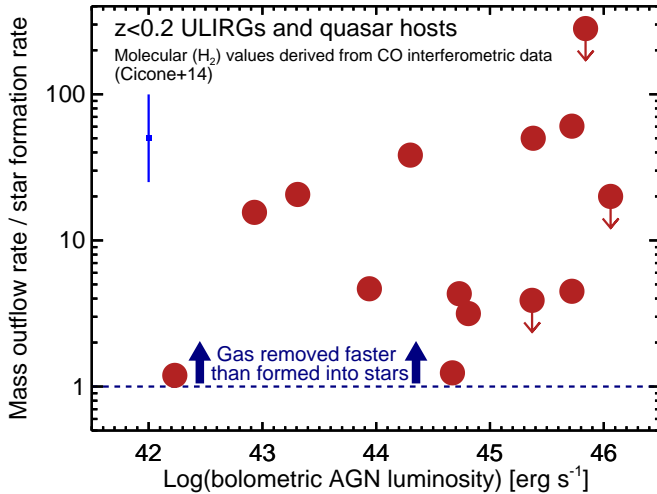


Figure 2 | Ratio of H₂ mass outflow rate to star formation rate as a function of AGN luminosity for low redshift ULIRGs and quasar host galaxies[50]. These measurements imply that molecular gas is being removed by AGN-driven outflows faster than it can be formed into stars. A representative error bar is shown in the top left, but this does not include the large and unknown uncertainty on converting CO to H₂ masses[50].

Radiatively-driven AGN outflows are known to be common on small spatial scales, i.e., close to the accretion disk, in the form of the extremely high speed winds that are identified in X-ray and ultra-violet spectroscopy (up to $v \approx 0.1-0.2 \times$ the speed of light[43, 44]). These winds have the potential to provide the feedback mechanism for self-regulating black hole growth (Box 1). Furthermore, lower velocity outflows in multiple gas phases (i.e., outflows of ionised, neutral and molecular gas) have been identified using one-dimensional spectra of AGN host galaxies and are more likely to be associated with host galaxy gas[45, 46, 47, 48]. In some cases these outflows are inferred to be located on 100s–1000s of parsec scales by applying a variety of modelling techniques, such as radiative transfer and photoionization models, to the information extracted from the spectra[47, 46]. What is even more pertinent is the direct detection of outflows on kiloparsec scales, in multiple gas phases, using spatially-resolved kinematic measurements[41, 49, 50, 51, 52]. Only if AGN can influence gas on \gtrsim kiloparsec scales will they be able to have a significant impact upon the galaxy-wide star formation in their host galaxies. Understanding how AGN accretion disk winds couple to multi-phase gas on galaxy-wide scales is an on-going observational and theoretical challenge[53, 54, 12].

Example evidence that AGN-driven outflows may have a significant impact upon star formation is that the measured mass outflow rates of molecular outflows in rare low redshift ultra-luminous infrared galaxies (ULIRGs) and quasar host galaxies appear to exceed the concurrent star-formation rates[50] (see Fig. 2). Consequently star-forming mate-

rial appears to be being removed more rapidly than it can be formed into stars in these galaxies. Similar arguments have also been made for more typical AGN host galaxies using a variety of gas tracers[55, 51]. However, there are various difficulties involved with deriving the measurements and performing these analyses, with dramatically different results possible when applying different techniques, making different assumptions or when using different gas tracers[51, 56, 57, 58]. Furthermore, understanding the timescale on which these outflows occur is troublesome and crucial for the interpretation on the long term impact of these outflows[58]. Particularly challenging is making these measurements beyond the local Universe, where, without excellent observations using adaptive optics or interferometers the spatial resolution can be comparable to, or higher than, the spatial extents of the outflows.

Towards a more direct indication that AGN-driven outflows may influence star formation, there have been observations of a small number of distant luminous AGN ($z \approx 1-3$) that show evidence for an anti-correlation between the spatial location of an ionised outflow and the location of narrow H α emission (a star-formation tracer)[59, 60]. These results may indicate that star formation has been reduced in the regions of the outflow, although an alternative possibility is that these diffuse outflows preferentially escape away from the dense star forming material[61]. Indeed, AGN-driven kiloparsec scale outflows are often found co-incident with high levels of on going star formation[50, 62]. In some cases, observational papers have also reported evidence of regions of enhanced star formation due to AGN-driven outflows or jets, and even suppression and enhancement working simultaneously in the same galaxies[63, 64].

Whilst much work has focussed on the idea that AGN should be able to evacuate galaxies of star-forming material, studies of nearby galaxies making use of (sub)-millimetre observatories have indicated that complete evacuation of cold molecular gas from a host galaxy is not a pre-requisite to shut down an intense star formation episode. Systems with a large molecular gas reservoir can be forming stars less efficiently than “typical” galaxies with the same molecular gas mass, potentially due to the injection of turbulence which inhibits the formation of gravitationally bound structures[65, 66, 67, 68]. In some sources AGN seem to be the most likely energy source[68, 66].

Observations have clearly identified that AGN can inject considerable energy/momentum into their host galaxies and investigation into the observable impact of this energy injection on star formation in individual galaxies is on-going. However, one of the greatest on-going challenges with these types of studies is to determine what long term impact AGN can have on their host galaxies. For example, even if measured outflow rates are very high (e.g., Fig. 2) and/or the star formation efficiencies are very low, it is not clear how long these episodes will last or if re-accretion of material will trigger future star formation. Furthermore, di-

rectly relating these episodes to the energy released by the central AGN is challenging due to the uncertain timescales of visible AGN activity and the resulting measurable impact (see Box 2). Insight may be obtained from *statistical* studies of the star formation properties of galaxies with and without a visible AGN.

Star formation properties of radiative AGN host galaxies

Towards assessing the impact of AGN on star formation, there has recently been an abundance of studies investigating the star formation rates of large samples of AGN host galaxies. Studies of purely mechanically-dominated AGN, at least for the most radio luminous, consistently find that they reside in low star-formation rate host galaxies[69, 70, 71]. However, for radiative AGN the conclusions have varied widely in the literature, with claims of star-formation rates that are: unrelated to AGN luminosity[72], enhanced for the most luminous AGN[73], inhibited for the most luminous AGN[74] or both enhanced and reduced depending on the wave-band used to trace the luminosity of the AGN[75, 76].

The conflicting conclusions for the star-formation rates of radiative AGN can largely be attributed to the different samples and approaches used. For example: (1) low numbers of the most luminous AGN can lead to statistical fluctuations; (2) it is difficult to convert photometric measurements into star formation rates (e.g., because of dust attenuation of optical and ultra-violet emission and the challenges of removing the AGN contribution to the emission at all wavelengths); (3) samples that only consider AGN that are detected in far-infrared surveys will be biased towards higher star-formation rates and (4) samples that are radio bright may contain both high star-formation rate radiative AGN and low star-formation rate mechanically dominated AGN. Another fundamental factor to consider, is how the underlying correlations between star-formation rate and both redshift and stellar mass are accounted for in each study. For example, a positive correlation between star formation rate and AGN luminosity may be driven by the fact that the most luminous AGN are hosted by the highest stellar mass galaxies.

The studies that contain some of the largest samples of AGN host galaxies, that have simultaneously taken into account redshift and stellar mass and that have applied uniform techniques across their samples find that average star-formation rates are independent of AGN luminosity[77, 78, 79, 80] (Fig. 3). Does this result indicate that radiative AGN have no positive or negative impact on galaxy-wide star formation rates? Addressing this question is non-trivial as it is extremely challenging to interpret the empirical result. As described in Box 2 the relative timescale of an AGN to be luminous compared to the timescale for any impact on the observed star formation rates are very uncertain. Furthermore, some models suggest that AGN are

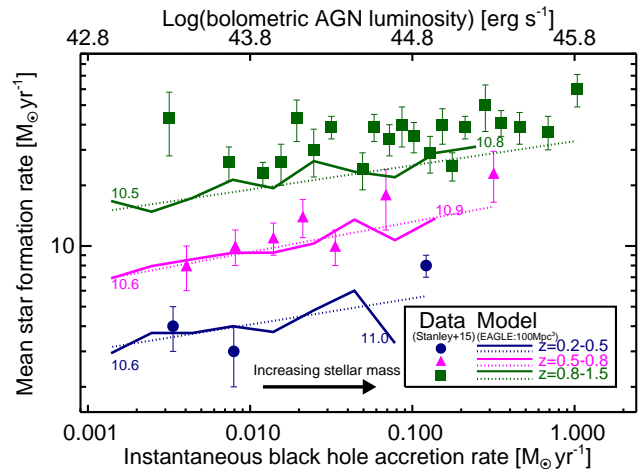


Figure 3 | Mean star formation rate versus instantaneous black hole accretion rate for a cosmological simulation[81] and versus AGN luminosity (converted from X-ray luminosities) for observations[79]. The dotted lines are a linear fit to the running means for the model (solid curves). The logarithm of the average 30 kpc aperture stellar masses (in stellar mass units) of the first and last bin are labelled; the slight increase in mean star-formation rate with increasing accretion rate is attributed to the increasing average stellar masses. Despite effective star-formation suppression by AGN in the model, this does not result in reduced average star-formation rates for the highest instantaneous black hole accretion rates (i.e., AGN luminosities).

unable to have a direct impact upon *concurrent* star formation but instead the cumulative effects of multiple AGN episodes may inhibit *future* star formation[61]. With these aspects in mind, it clearly limits what can be inferred from the star-formation rates of AGN without complementary theoretical predictions.

It is informative to obtain a prediction on the star formation rates of AGN from a cosmological model that requires the suppression of star formation during periods of rapid black hole growth to reproduce observable galaxy properties. For example, in agreement with the data, the reference model of the EAGLE simulations (that includes thermal energy injection from AGN)[82] shows no evidence for reduced average star formation rates with increasing black hole accretion rate[81] as shown in Fig. 3. In Fig. 3: the star formation rates are galaxy-wide, are averaged over 100 Myrs to broadly match the observed far-infrared measurements and are shifted up by 0.2 dex, to account for a systematic offset seen for all galaxies in the simulation; the instantaneous black hole accretion rates are converted to bolometric AGN luminosities assuming a radiative efficiency of 10% (all details in [81]). Due to accretion rate variations that happen more rapidly than the star formation rate variations, the effects of star formation suppression does not result in a negative trend in the star-formation rate versus AGN luminosity plane. Although based on a single model, this test highlights that it is not possible to

conclude a lack of impact by AGN upon star formation based purely upon an empirical result where average star-formation rates are not reduced for galaxies that host the most instantaneously luminous AGN.

Further insight will be gained on this topic by analysing the full distributions of star formation rates (not just simple averages) for radiative AGN host galaxies[83, 78, 84, 71, 70] in the context of theoretical predictions. Furthermore, further work using detailed spectra to assess the star formation *histories* of AGN host galaxies, in tandem with specific model predictions on how AGN and star formation interact, will also provide insight into the observable signatures of the impact of AGN[85, 86]. However, as I will suggest in the next section investigating the massive galaxy population as a whole, irrespective of the presence of a luminous AGN, may yield some of the most informative results on the impact of AGN on star formation.

Star-formation rates of massive galaxies

As already described, it is a popular and effective method in galaxy formation models to invoke AGN to reduce the star formation of the most massive galaxies (Fig. 1). Even the most simple “empirical” galaxy formation models require some process to “quench” the most massive galaxies[87]. Therefore, insight into the impact of AGN on star formation may be gained from investigating the star-formation rates as a function of stellar mass. In the star-formation rate versus stellar mass plane, galaxies are generally classed into two categories; “star-forming galaxies” that follow a relatively tight positive relationship between star-formation rate and stellar mass and “quiescent galaxies” that fall below this relationship, where the fraction of quiescent galaxies increases with stellar mass[16, 88, 89].

Recent work has shown that star-forming galaxies with low stellar masses, i.e., below $\lesssim \text{few} \times 10^{10} M_{\odot}$, follow an almost linear relationship between average star-formation rate and stellar mass whilst more massive star-forming galaxies, both with and without a luminous AGN, have a shallower slope[89, 90, 91] (Fig. 4). This reveals that the star-formation rates per unit mass are smaller in the galaxies above this stellar mass threshold. This effect is observed to already be in place ≈ 3 Gyrs after the Big Bang (redshift $z \approx 2$) although the exact form of the star-formation rate versus stellar mass relationship evolves with time[88, 89, 90] (Fig. 4). Consequently, it is a useful exercise to investigate the role of AGN in reducing the relative growth rates of the most massive galaxies using model predictions.

Fig. 4 shows the running average star-formation rate as a function of stellar mass of galaxies from two runs of the cosmological hydrodynamical EAGLE simulations; the 50 Mpc^3 box reference model (where AGN are effective in regulating star formation) and an identical run, except where AGN are “turned off”[82, 11]. Following [81], the star formation rates are total values and the stellar masses are 30 kpc aperture values (taken from the EAGLE

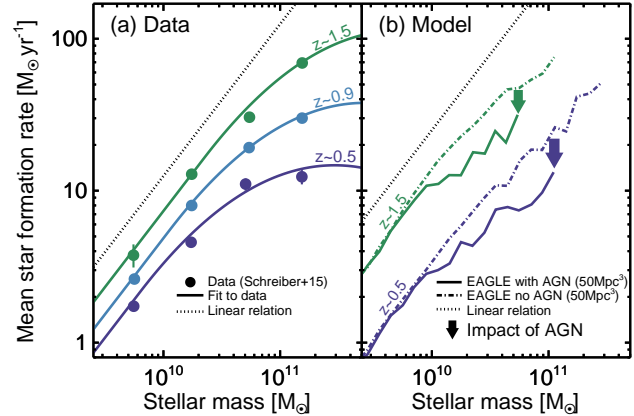


Figure 4 | Mean star formation rate versus stellar mass for observed star-forming galaxies[90] (a) and galaxies in a cosmological model run both with and without AGN[82, 11] (b). More massive galaxies form stars more rapidly; however, the highest-mass galaxies ($M_{\text{stellar}} \gtrsim 10^{10} M_{\odot}$) are observed to fall below a constant scaling relationship implying a reduction in the ability for the available baryons to be converted into stars[89, 90]. In the model, the impact of AGN is to reduce star formation rates of high mass galaxies as well as to reduce the overall number of massive galaxies. Note that error bars are smaller than the data points in most cases[90].

database[92]). Averages are only calculated for stellar mass bins containing more than 15 galaxies. These two runs of the same simulation provide qualitative insight into the impact of AGN on the observed star-formation rate versus stellar mass plane (Fig. 4). In the model, it can be seen that AGN are responsible for creating a shallower slope at the highest stellar masses as well as reducing the overall number of massive galaxies[82, 11]. The builders of the Horizon-AGN hydrodynamical cosmological simulation recently performed a similar test by running the simulation with and without AGN feedback and came to the same conclusion: the effect of AGN is to significantly reduce the star formation rates of massive galaxies with the magnitude of suppression increasing with stellar mass[93]. Therefore, it appears that the observational signature of AGN suppressing star formation may be imprinted on the reduced average star formation rates per unit stellar mass for the most massive galaxies (Fig. 4) and *not* on reduced average star formation rates for the most instantaneously luminous AGN (Fig. 3).

The results described above, and other recent work, highlight that investigating the star formation properties for populations of massive galaxies, not just AGN-host galaxies, at multiple cosmic epochs is a critical test for different AGN feedback prescriptions[94, 95, 96, 97].

Conclusions

Some of the key conclusions brought up in this review are:

(1) Local mechanically-dominated AGN are energetically capable of regulating gas cooling on large scales via radio jets in the most massive haloes and consequently regulating star formation inside their host galaxies. However, it is uncertain what “quenched” the high levels of star-formation that previously occurred in these galaxies and what role these AGN play at early cosmic epochs ($z \gtrsim 0.5$) and in less dense environments.

(2) Radiative AGN are observed to be driving outflows in multiple phases of gas. For many galaxies, measurements of energy and mass outflow rates have implied that star formation could be suppressed by the removal of star-forming material. However, the long-term impact of these events is unclear. In a few cases AGN-driven jets are also observed to be triggering local episodes of star formation.

(3) The suppression or regulation of star-formation by an AGN does not need to be the result of the complete evacuation of gas from a galaxy. Observations of turbulence, shocks and heating by AGN jets and outflows suggest that they are able to reduce the efficiency of converting the available gas supply into stars without the need to remove it.

(4) The most massive galaxies ($M_{\text{stellar}} \gtrsim 10^{10} M_{\odot}$) have low star formation rates per unit stellar mass across multiple cosmic epochs. Although not conclusive, this could be due to star formation suppression by the cumulative effect of AGN episodes.

(5) The timescales of various feeding and feedback processes remain uncertain. For example, AGN may no longer be visible or luminous when the impact that they have had becomes observable. Consequently, great care must be taken when using empirical results to draw conclusions on “smoking gun” evidence for or against the impact of AGN upon star formation. Whilst we may observe the “smoke” (e.g., outflows and/or reduced star formation rates) the “gun” (i.e., the AGN) may no longer be visible.

Future prospects

Further work combining *specific* theoretical predictions with observations is required to make significant progress in understanding the long term impact of AGN on their host galaxies. Hydrodynamical cosmological models provide the means to make predictions on the star-formation properties and their evolution of statistical samples of galaxies using a variety of feedback models. In parallel to this, high-resolution simulations can indicate what the observational signatures are for various mechanisms of how AGN could transfer energy and momentum into the gas in individual galaxies.

From observations, over the next five to ten years we can expect to see considerable progress in the number of high-quality measurements to test these models. For example, the upgrade of (sub)-millimetre interferometers such as ALMA and NOEMA will produce sensitive, high resolution

observations of dust emission and molecular gas in an increasing number of sources across multiple cosmic epochs. Such observations will significantly reduce the uncertainties on derived quantities such as star formation rates and mass outflow rates. Forthcoming facilities such as *JWST* (due to be launched in 2018) and 30m-class telescopes (expected first light in the early 2020s) will enable us measure gas inflows, outflows and host galaxy properties (such as stellar masses and star-formation histories), to unprecedented precision for large samples of extremely distant galaxies ($z \gg 1$). Furthermore, the data from *eROSITA* (due to be launched in 2018) will yield X-ray identification of millions of AGN, which could provide a key role in testing model predictions on large, statistical samples of AGN host galaxies.

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