Impact of supermassive black hole growth on star formation

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Supermassive black holes are found at the centres of massive galaxies. During the growth of these black holes they light up to become visible as active galactic nuclei (AGNs) 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 remain uncertain from both an observational and theoretical perspective. I review some of the theoretical motivation and observational results and discuss possible observational signatures of the impact of supermassive black hole growth on star formation.

The discovery that all massive galaxies host a central supermassive black hole 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 (~10⁶–10¹⁰ M☉), primarily grow through periods of radiatively efficient accretion of gas when they consequently become visible as AGNs. Historically, AGNs were considered rare but fascinating objects to study in their own right, yet over the last two decades these phenomena have moved to the forefront 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. However, arguably the most influential factor in the explosion of interest in AGNs are the results from galaxy evolution models.

Most galaxy formation models require AGNs to inject energy or momentum into the surrounding gas (Box 1) in the most massive galaxies (that is, with stellar masses Mstellar ≥ 10¹¹ M☉), in order to reproduce many key observables of galaxy populations and intergalactic material.1–12 (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 (Fig. 1); the tight relationships between black hole masses and galaxy bulge properties1 and the formation of quiescent bulge-dominated massive ‘red’ galaxies that are no longer forming stars at significant rates15.

AGNs are an attractive solution in models to supply the energy required to explain the observations. By releasing ~10% of the rest mass energy of accreted material, they are phenomenal energy sources4–7. For example, during the formation of a ~10⁶ M☉ black hole ~10⁴ 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 star formation in the host galaxy (Box 1).

While it is theoretically attractive to invoke AGNs 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 the resulting impact this has on star formation in the AGN host galaxies.

Methods of energy injection by AGNs
The energy released by an AGN (through black hole accretion) may be radiative (that is, energetic photons) or mechanical (that is, energetic particles). In models, radiative energy injection is sometimes called ‘quasar’ or ‘wind’ mode and is usually associated with high Eddington ratios of ≥0.01. This means that the mass accretion rates are ≥1% of the theoretical maximum ‘Eddington limit’, where the Eddington limit is the outward force due to radiation pressure on electrons equals the inward force due to gravity on the protons (assuming a spherical geometry). 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 the coupling of accretion radiation to the gas on small scales, to explain the observed scaling relationships between galaxies and black holes. In hydrodynamical simulations energy injection from AGNs is often crudely implemented; for example, by assuming a small fraction of the total radiative luminosity of accreting black hole couples thermally to the surrounding gas, with the result of expelling material from the host galaxy in an outflow and suppressing star formation. However, recently simulations have incorporated more complex prescriptions for ‘feedback’ by invoking and testing multiple modes of energy injection. Observational constraints on the different feedback prescriptions are a critical test of these models.

Based on the above, it is convenient to classify observed AGNs into two broad categories: those for which their energetic output is predominantly radiative (radiative AGNs) and those for which it is predominantly mechanical (mechanically-dominated AGNs). Radiative AGNs 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 (~1% of all galaxies). Mechanically-dominated AGNs are usually identified through luminous radio emission; however, those identified are found in the most massive systems and a rare subset of all galaxies that host low black hole accretion rates.

Mechanically-dominated AGNs are predominantly found in the most massive galaxies (Mstellar ≥ 10¹¹ M☉) with old stellar populations,
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 available 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 ionizing, 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 Review Article is to explore the observational results concerning the impact of black hole growth on star formation.

Schematic diagram illustrating the relationships between fuel supply, galaxy growth and black hole growth.

at least in the local Universe, while radiative AGNs are most common in galaxies with ongoing star formation and younger stellar populations at all cosmic epochs. 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. Therefore, when assessing the impact of AGNs on star formation it is important to consider these AGN types separately. Care is especially required for AGNs identified through luminous radio emission that are increasingly more mechanically dominated towards later cosmic times (that is, redshifts $z \leq 1$) and are increasingly more radiatively dominated at early cosmic times.

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 AGNs can maintain host galaxy star formation at low levels. This is achieved by suppressing the ability for hot gas to cool (Box 1) and has been reviewed extensively in the literature. However, it is not yet fully understood what role AGNs play in less dense environments or if gas needs to be ejected during earlier AGN episodes for these mechanically dominated AGNs to be effective at regulating gas cooling. 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 and it is not yet clear what quenched the earlier high rates of star formation in these systems. Furthermore, the role and mechanisms of AGN feedback during a galaxy’s formation may be different for galaxies with different final masses and morphologies.

To work towards addressing the outstanding issues raised above and to fully characterize the impact of AGNs on star formation, it is crucial to study and understand the role of radiative AGNs. This is particularly true at early cosmic times (that is, $z \geq 0.5$), when significant levels of black hole and galaxy growth were occurring. The remainder of this Review Article will focus on the observational evidence for the impact of radiative AGNs 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.

**Observations of energy injection by radiative AGNs**

A common approach to understanding the impact of AGNs on star formation is to search for and to characterize a mechanism by which AGNs are injecting energy and/or momentum into the gas in their host galaxies (Box 1). For example, outflows may remove gas from the host galaxy and have the effect of suppressing star formation.

**Box 1 | The cycle of matter and growth in galaxies.**

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 available 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 ionizing, 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 Review Article is to explore the observational results concerning the impact of black hole growth on star formation.

**Figure 1 | Average ratio of stellar mass to halo mass as a function of halo mass for three runs of a simulation and for the semi-empirical relationship.**

The model in ref. 6 is used to simulate the cases of no feedback (squares), star formation (SF) feedback (triangles) and combined SF and AGN feedback (circles). The shaded region shows the 16th and 84th percentiles of the fiducial model that includes energy injection from AGNs and SF. The right y axis shows the efficiency for turning baryons into stars ($\text{M}_\text{star} / [f_b \times \text{M}_\text{halo}]$, where $f_b = 0.17$ is the cosmological baryon fraction). SF feedback reduces the efficiency of star formation in low-mass haloes. For massive haloes, AGNs are required to reduce these efficiencies and to reproduce many observables of the galaxy population.

![Schematic diagram illustrating the relationships between fuel supply, galaxy growth and black hole growth.](image-url)
Alternatively, AGNs 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 Article to comprehensively cover the huge amount of observational work on outflows or jets driven by radiative AGNs (see refs 12,34,40,41). However, below I focus on some of the observational work that specifically investigates the impact that these outflows may have on star formation.

Radiatively-driven AGN outflows are known to be common on small spatial scales, that is, close to the accretion disk, in the form of the extremely high-speed winds that are identified in X-ray and ultraviolet spectroscopy (up to speeds \( v \approx 0.1–0.2c \))42,43. 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 (that is, outflows of ionized, 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 gas44–46. In some cases these outflows are inferred to be located on scales of hundreds to thousands of parsecs by applying a variety of modelling techniques, such as radiative transfer and photoionization models, to the measurements extracted from the spectra47–49. What is even more pertinent is the direct detection of outflows on kiloparsec scales, in multiple gas phases, using spatially resolved kinematic measurements40,44–46,49. Only if AGNs can influence gas on \( \gtrsim \) kiloparsec scales will they be able to have a significant impact on galaxy-wide star formation in their host galaxies. Understanding how AGN accretion disk-winds couple to multiphase gas on galaxy-wide scales is an ongoing observational and theoretical challenge12,23,50.

Example evidence that AGN-driven outflows may have a significant impact on 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 rates9 (Fig. 2). Consequently, star-forming material 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 tracers50,54. 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 tracers50,55–57. Furthermore, understanding the timescale on which these outflows occur is troublesome and crucial for the interpretation of their long-term impact57. Making these measurements beyond the local Universe is particularly challenging, where, without observations using adaptive optics or interferometers, the spatial resolution can be comparable to, or larger 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 AGNs ( \( z \approx 1–3 \)) that show evidence for an anti-correlation between the spatial location of an ionized outflow and the location of narrow H\( \alpha \) emission (a star formation tracer)36,39. 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 material60. Indeed, AGN-driven kiloparsec-scale outflows are often found coincident with high levels of ongoing star formation49,51. 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 galaxies52,61.

While much work has focused on the idea that AGNs 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 prerequisite 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 that inhibits the formation of gravitationally bound structures44–47. In some sources AGNs seem to be the most likely energy source55,62.

Observations have clearly identified that AGNs can inject considerable energy/momentum into their host galaxies and investigate into the observable impact of this energy injection on star formation in individual galaxies is ongoing. However, one of the greatest ongoing challenges with these types of studies is to determine what long-term impact AGNs can have on their host galaxies. For example, even if measured outflow rates are very high (for example, see 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, directly 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 (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 AGNs 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 AGNs, at least for the most radio luminous, consistently find that they reside in low star-formation-rate host galaxies\(^{44-70}\). However, for radiative AGNs the conclusions have varied widely in the literature, with claims of star formation rates that are: unrelated to AGN luminosity\(^{71}\), enhanced for the most luminous AGNs\(^{72}\), inhibited for the most luminous AGNs\(^{73}\) or both enhanced and reduced depending on the wave band used to trace the luminosity of the AGN\(^{74-75}\).

The conflicting conclusions for the star formation rates of radiative AGNs can largely be attributed to the different samples and approaches used. For example: (1) low numbers of the most luminous AGNs can lead to statistical fluctuations; (2) it is difficult to convert photometric measurements into star formation rates (for example, because of dust attenuation of optical and ultraviolet emission and the challenges of removing the AGN contribution to the emission at all wavelengths); (3) samples that only consider AGNs 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 AGNs and low star-formation-rate mechanically dominated AGNs. 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 AGNs 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\(^{76-78}\) (Fig. 3). Does this result indicate that radiative AGNs 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, both the timescale for an AGN to remain luminous and the time delay between the onset of luminous activity and any consequent observable impact on the host galaxy’s star formation rate are very uncertain. Furthermore, some models suggest that AGNs are unable to have a direct impact on concurrent star formation but instead the cumulative effects of multiple AGN episodes may inhibit future star formation\(^{79}\). With these aspects in mind, it clearly limits what can be inferred from the star formation rates of AGN host galaxies without complementary theoretical predictions. It is informative to obtain a prediction of the star formation rates of AGNs 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 (Evolution and Assembly of GaLaxies and their Environments) simulations (that includes thermal energy injection from AGNs)\(^ {80}\) shows no evidence for reduced average star formation rates with increasing black hole accretion rate\(^ {81}\), as shown in Fig. 3. The star formation rates shown in Fig. 3 are galaxy-wide, averaged over 100 Myr 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 and the instantaneous black hole accretion rates are converted to bolometric AGN luminosities assuming a radiative efficiency of 10% (see ref. \(^ {81}\) for details). In the model, AGNs do suppress star formation; however,
accretion rate variations happen more rapidly than star formation rate variations. Consequently, the luminosity of the AGNs may have reduced by orders of magnitude before the star formation rates are significantly reduced. Therefore, a negative trend between star formation rate and AGN luminosity is not observed in the model. Although based on a single model, this test highlights that it is not possible to conclude a lack of impact by AGNs upon star formation based purely on an empirical result where average star formation rates are not reduced for galaxies that host the most instantaneously luminous AGNs.

Further insight will be gained on this topic by analysing the full distributions of star formation rates (rather than just simple averages) for radiative AGN host galaxies86–88,91,92,93 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 AGNs and star formation interact, will also provide insight into the observable signatures of the impact of AGNs84,85. However, as I will suggest in the next section, investigations of massive galaxy populations as a whole, irrespective of the presence of a luminous AGN, may yield some of the most informative results on the impact of AGNs 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 AGNs 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 galaxies94. Therefore, insight into the impact of AGNs on star formation may be gained from investigating the star formation rates as a function of stellar mass. Within this context, 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 mass95,96,97.

Recent work has shown that star-forming galaxies with low stellar masses, that is, ≤ a few × 10^10 M⊙, follow an almost linear relationship between average star formation rate and stellar mass, while more massive star-forming galaxies, both with and without a luminous AGN, have a shallower slope98–90 (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 Gyr after the Big Bang (redshift z ~ 2), although the exact form of the star formation rate versus stellar mass relationship evolves with time97–99 (Fig. 4). Consequently, it is a useful exercise to investigate the role of AGNs in reducing the relative growth rates of the most massive galaxies using model predictions.

**Figure 4** shows the running average star formation rate as a function of the stellar mass of galaxies from two runs of the cosmological hydrodynamical EAGLE simulations: the 50 Mpc^3 box reference model (where AGNs are effective in regulating star formation) and an identical run, except where AGNs are ‘turned off’11,90. Following the procedure described in ref. 81, the star formation rates are total values and the stellar masses are 30 kpc aperture values (taken from the EAGLE database93). Averages are only calculated for stellar mass bins containing more than 15 galaxies. Figure 4 demonstrates that these two runs of the same simulation provide qualitative insight into the impact of AGNs on the star formation rates of all galaxies. In the model, it can be seen that AGNs are responsible for creating a shallower slope at the highest stellar masses as well as reducing the overall number of massive galaxies11,90. 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 AGNs is to significantly reduce the star formation rates of massive galaxies with the magnitude of suppression increasing with stellar mass95.

Therefore, if AGNs suppress star formation this may not result in reduced average star formation rates for the most instantaneously luminous AGNs (Fig. 3), but instead the signature of this effect may be imprinted on the reduced average star formation rates per unit stellar mass for the most massive galaxies (Fig. 4).

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 prescriptions15,96.

**Conclusions**

The following are some of the key conclusions brought up in this Review Article.

1. Local mechanically dominated AGNs 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 AGNs play at early cosmic epochs (z ≥ 0.5) and in less dense environments.

2. Radiative AGNs 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.
Gaspari, M., Melioli, C., Brighenti, F. & D’Ercole, A. The dance of heating and feedback processes remain uncertain. For example, AGNs 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 AGNs upon star formation. While we may observe the ‘smoke’ (for example, outflows and/or reduced star formation rates) the ‘gun’ (that is, 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 AGNs on their host galaxies. Hydrodynamical cosmological models provide the means to make predictions on the star formation properties and the evolution of statistical samples of galaxies using a variety of feedback models. Parallel to this, high-resolution simulations can indicate the observational signatures for various mechanisms through which AGNs 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 (Atacama Large Millimeter/submillimeter Array) and NOEMA (NORTHERN Extended Millimeter Array) 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 the James Webb Space Telescope (due to be launched in 2018) and 30-m-class telescopes (expecting first light in the early 2020s) will enable us to 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 > 1). Furthermore, the data from eROSITA (Extended Roentgen Survey with an Imaging Telescope Array; due to be launched in 2018) will yield X-ray identification of millions of AGNs, which could provide a key role in testing model predictions on large, statistical samples of AGN host galaxies.

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Additional Information

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Competing interests

The author declares no competing financial interests.