Lecture 15:
AGN feedback and outflows

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1 Introduction

Over the past few lectures we've looked extensively at supermassive black holes (SMBH) and the AGN that are produced when these black holes accrete matter. However, while you may have (hopefully) found AGNs interesting in their own right, you may be asking yourself what they've got to do with galaxy evolution. In this lecture, we will be addressing that very question.

2 Indirect evidence of links between AGN and galaxy evolution

As you should probably be aware by now, no AGN is in complete isolation: as the name suggests, they're all found in the centres of galaxies. Furthermore, we saw in the previous lecture that the trigerring of AGNs is intrinsically linked to their host galaxies since all accreted material ultimately comes from the host. Indeed, we saw that it's likely that some AGNs are triggered by galaxy interactions. As such, there is clearly at least some level of co-evolution between AGNs and their host galaxies.

Until the mid-1990's, this "co-existence" picture of AGNs and galaxies formed pretty much our whole understanding of the relationship between AGNs and their host galaxies. However, toward the end of that decade and into the mid 2000's, a number of major discoveries were made in AGN astronomy that suggest that the relationship between AGNs and their host galaxies is much closer than previously thought.

2.1 Evidence from observations

The first of these discoveries was that the masses of supermassive black holes are tightly correlated with the masses of their host galaxy bulges. As we saw in Lecture 12 (§4.4), this tight correlation is remarkable because the gravitational influence of the black hole only dominates within a few tens of parsecs, meaning that – gravitationally at least – the vast majority of stars within the galactic bulge "knows" nothing of the black hole in the centre.[1] The tight correlation between black hole mass and bulge mass has been interpreted as evidence of a level of interaction between the two *beyond* that expected from gravity alone.

The second discovery that was interpreted as signalling a strong evolutionary link between SMBHs/AGNs and galaxies is that the star formation rate density and the black hole accretion rate

[1] It should go without saying that, in terms of gravity, the black hole known nothing of the bulge. Gauss's theorem tells us that.

density of the Universe have evolved "in-sync" over the entire observable history of the Universe. As such, by one way or another, the total amount of material accreting onto a SMBH (during an AGN episode) at any epoch is closely tied to the total amount of material that forms stars. This is seen as clear evidence that black holes and galaxies have co-evolved over the past 13 billion years.

2.2 Evidence from simulations

The final major discovery linking AGNs to galaxy evolution that we will consider came not from observations, but from computer simulations (or, more correctly, from comparing the predictions made by computer simulations against observations). One of the most important – and reliable – outcomes of cosmological-scale, dark-matter dominated semi-analytic models is the mass function of dark-matter halos.[2] It is "reliable" because dark matter only interacts with itself and other matter via gravity, which we understand *very* well on cosmological scales. What semi-analytic models predict is that the dark-matter halo mass function can be described very well as a simple power law (i.e., a straight line on a log-log plot). Of course, we can't actually measure the dark matter mass function to compare against this prediction, so instead we to use analytic prescriptions to populate the dark matter halos with galaxies which we can then compare to the (measured) *galaxy* mass function.

The prescriptions used in the first truly cosmological-scale semi-analytic models (in the mid-2000s) predicted that the galaxy mass function was very different to that observed in the real Universe. In particular, the first simulated mass functions hugely overpedicted the numbers of very low mass and very high mass galaxies in today's Universe (by many orders of magnitude). In fact, the earliest simulated galaxy mass functions were also well-described by a single power-law, whereas as we have seen throughout the course, the observed mass function is better described by a broken power law (or, more specifically, a Schechter function). It became clear that what was needed was a way to prevent too many very low and very high mass galaxies from forming within the dark matter halos.

The way to prevent a galaxy from forming or getting bigger is to prevent gas from cooling and collapsing to form stars. This is done by injecting energy into the gas to either heat it up or drive it out of the gravitational potential well that is pulling it together. At the time of the first simulations, it was already known that a major source of energy input is from stars themselves, in the form of stellar winds, supernovae and simply radiation from the photosphere. However, when this "feedback" from stars was included in the semi-analytic models, it was found they only solve one part of the problem: they only prevent the formation of too many small galaxies. In order to prevent too many *massive* galaxies from forming, much more energy needs to be injected. It was found that by including (reasonable levels of) energy from AGNs in the semi-analytic models prevented gas from collapsing and forming too many massive galaxies, and closely reproducing the observed galaxy mass function. As such, the comparison between the galaxy mass function predicted by semi-analytic models and that observed in the real Universe provides indirect evidence of "feedback" processes (both stellar and AGN in origin) regulating galaxy growth.

Further indirect evidence of "AGN feedback" came from smaller-scale simulations of merging galaxies. Around the same time that cosmological-scale semi-analytic models were predicting the need for AGN feedback (i.e., mid-2000s), simulations of galaxy interactions were also providing evidence of a link between AGNs and their host. In these smaller-scale simulations, it was found

[2]In the same way that there is a galaxy mass function – simply the histogram showing the numbers of galaxies in a given mass bin per unit volume – there is a dark matter halo mass function.

that, unless energy from an AGN was used to "sweep-out" the gas from a galaxy post-major merger, then the resulting galaxies were far too compact (compared to real galaxies) and did not reproduce the observed black-hole to bulge mass correlation.

3 How might AGNs affect galaxy evolution

The indirect evidence of a close link between AGNs and galaxies highlighted above caused a significant shift in our consideration of AGNs. In the space of a decade, AGNs went from being studied as a mere "curiosity" to being regarded as having a major impact on how galaxies have evolved.

Despite their perceived importance, it remains unclear precisely *how* AGNs affect galaxy evolution in the *real* Universe. Although we know that AGNs produce a lot of energy, it's not clear how (or even whether) this energy is effectively transferred into their host galaxies to affect a change. However, simulations do predict two key mechanisms:

- Heating gas on large (i.e., dark matter halo) scales which prevents it from cooling and collapsing toward the centre of the halo (where the galaxy lives) and forming stars;
- Heating-up or driving-out the cool gas already within the galaxy which *would* have formed stars.

Of course, it is also possible that once gas driven out by the second mechanism reaches large enough scales it is prevented from re-cooling by the first mechanism. In the following sections, we'll look in more detail at the observational evidence supporting these two mechanisms.

4 Heating inter-galactic gas

To heat inter-galactic gas (i.e., the gas *between* galaxies), an AGN would be required to have an influence on the environment well outside its host galaxy. In other words, on scales of tens to thousands of kiloparsecs (remember, a galaxy is a few tens of kpc across, while the distances between galaxies are typically measured in megaparsecs). These are the kinds of scales that are reached by the jets of radio-powerful AGNs, so these provide an obvious potential means for an AGN to influence the inter-galactic material.

With clear observational evidence of kpc to Mpc scale radio jets being produced by AGNs, the next key question is: do these jets actually heat the inter-galactic material and prevent it from cooling onto the host galaxy where it can form stars? One way this could be achieved is via *shock heating*. Shocks occur when discontinuities in gas pressure and density move though a medium (in this case the inter-galactic gas) at speeds faster than the local sound speed. When this happens, the atoms of gas are accelerated at the interface of the discontinuity, which heats up the gas.

The plasma from which AGN jets are formed are travelling at close to the speed of light, so much, much faster than the local sounds speed of the inter-galactic material (which is typically around 300 km s^{-1}. As such, these jets generate shockwaves that expand outward from the jet as it advances through the intergalactic material. Importantly, the shock waves expand spherically around the progressing jet, so are not just confined to the small opening angle of the jet and, instead, will propagate throughout the surrounding intergalactic material. These advancing shocks are predicted to heat the intergalactic material to $\sim 10^6$ K, which is easily high enough to prevent it from cooling onto the galaxy.

Do we actually see any evidence of AGN-launched jets actually transmitting shockfronts into the intergalactic gas? At temperatures of 10^6 K, gas emits X-rays as an extremely hot black body. By observing inter-cluster gas around radio AGNs, astronomers have indeed found evidence of extremely hot, shocked gas forming "bow-shocks" around the the collimated radio jets. Crucially (and as expected) these shocks have a much larger opening angle compared to the highly collimated jets, so display clear evidence of radio jets transmitting large amounts of energy into large volumes of the inter-cluster material. This energy is, indeed, heating the gas up to millions of Kelvin, preventing it from cooling to form stars.

Another way that AGN-launched radio jets can affect the inter-cluster gas is by also physically moving the gas away from the galaxy. In this scenario, the jets excavate cavities of gas which is similar, in principle, to blowing up a bubble. The energy contained within these bubbles is sufficient to prevent the cooler gas outside the bubble from cooling and falling onto the host galaxy. Such bubbles of hot gas are, indeed, seen in X-rays behind the shock waves caused by the propagating jet.

5 Affects on the inter-stellar material

As well as preventing gas *outside* the galaxy from cooling and collapsing to form stars, it is thought that AGNs may also affect the gas *within* the host galaxy; the so-called inter-stellar material. After all, a typical AGN produces many times more energy than is required to disrupt (i.e., ionise, heat, eject) the *entire* gas content of a galaxy. In order to do so, however, a significant fraction of this energy must be captured by the interstellar gas. It remains to be determined whether the coupling between the energy released by AGNs and the interstellar gas is sufficient to prevent the latter from forming stars.

There are two main mechanisms by which astronomers think that AGNs are affecting the interstellar gas in their host galaxies: one is via radio jets (again) and the other is via non-relativistic "winds". Both, ultimately, lead to the same result: the evacuation of interstellar gas from the host galaxy.

5.1 Jet-ISM interaction

As well as the huge, Mpc-scale radio jets displayed by some AGN (in fact, a minority of about 10%), many more show evidence of compact radio emission. On closer inspection, these compact radio AGNs do display evidence of radio jets, but they are typically extended on sub-kpc (rather than Mpc) scales. As such, these jets are extended on galaxy-scales.

What is particularly interesting about these galaxy-scale jets in terms of AGN feedback is that optical spectroscopy has revealed that they are often associated with high-velocity gas in the interstellar material.[3] It is not unusual for this gas to have speeds of 1000 km s^{-1} or more, but they are *not* relativistic. In other words, this is *not* the plasma that is forming the jets, but is instead interpreted as interstellar material that is being accelerated to many hundreds of km s^{-1} *by* the jet. Based on reasonable (but highly uncertain) assumptions about its density, this jet-accelerated interstellar material is thought to be outflowing at a rate of many hundreds (and in some cases up to thousands) of solar masses per year. If this is maintained over a the expected lifetime of an AGN of a few tens of millions of years, this could, in principle result in around 10^{10} $M_\odot$ of gas

[3]Recall that we can extract the kinematics of the gas from the profiles of its emission lines.

being evacuated from the host galaxy – enough to have a significant impact on the future growth of the galaxy.

5.2 AGN "winds"

So far, we've seen that radio powerful AGNs are prime candidates for "AGN feedback". However, only a minority of AGNs are radio loud, so what about the dominant population of radio-quiet AGNs? Are they thought to induce "AGN feedback"? If so, has this been confirmed by observations?

In previous lectures, we've seen how an AGN (radio quiet or otherwise) can produce the same amount of light as an entire galaxy in a region of space only a few times bigger than our solar system. Not only that, but a lot of this light is emitted in the UV. This concentration of energy production is truly staggering, and leads to some intense physical processes. One of the most interesting of these in terms of AGN feedback are "AGN winds".

It is thought that one of the consequences of the intense heat and radiation of the accretion disk is that it "boils off" large quantities of gas (possibly as much as half of the mass of the accretion disk may evaporate in this way). This is not dissimilar to stellar winds being driven-off massive stars. As soon as the gas rises out of the accretion disk, it is subject to the full intensity of the radiation from the disk and is accelerated from the accretion disk via photon pressure. This gas can reach speeds of tens of thousands of km s^{-1} very close to the central engine, but as they travel outwards they lose velocity due to gravity (from the stars in the galaxy) and because they crash into the ambient interstellar gas. However, despite their loss of speed, it is still predicted that they are sufficiently powerful to eject a substantial amount of the interstellar gas from the host galaxy.

But do we *see* any evidence of such AGN winds among radio-quiet AGNs? The answer is an emphatic Yes. Indeed, roughly a fifth of all quasars show clear evidence of broad, blushifted absorption lines in their rest-frame UV spectra. It is not unusual for these absorption lines to be shifted by many tens of thousands of km s^{-1}, meaning that the absorbing gas is moving *toward* us (relative to the host galaxy) at an incredibly high speed. This has been interpreted as clear evidence of gas *outflowing* along our line of sight toward the central engine. Due to the levels of variability displayed by these lines, it is thought these they trace outflows with roughly 10 pc of the central engine.

At even smaller scales (and higher energies), there is evidence of even faster winds in X-ray observations. These show absorption features that are blueshifted by many tens of thousands of km s^{-1} (the fastest are approaching relativistic speeds). Again, these are interpreted as providing evidence of extremely fast moving outflows on scales of less than 1 pc from the central engine. Further, the amount of mass contained within these "ultra fast outflows" is an appreciable fraction of the Eddington luminosity of the SMBH.

So, there is clear evidence that radio-quiet AGNs do, indeed, drive powerful outflows. However, until fairly recently, these discoveries were limited to small scales, whereas for an AGN to influence galaxy evolution these outflows must interact with the interstellar material on kpc-scales. Recently, however, integral field observations of AGNs both in the local Universe and in the high-redshift Universe show evidence of strongly blueshifted *emission* lines on kpc scales. Again, this has been interpreted as evidence of AGN-driven outflows, but with velocities somewhat lower than those observed in UV and X-ray absorption lines. Despite this, they still show evidence of outflowing gas travelling at hundreds or, in some cases, thousands of km s^{-1} on *galactic* scales. It is thought that these outflows are in the processes of sweeping-out the interstellar material within the host galaxy, and thereby quenching future star-formation. However, finding galaxy-scale outflows is one thing, but actually *proving* that *quenching* is actually taking place is proving to be far more of a challenge and is currently one of the hottest topics in extragalactic astronomy research.

6 Learning objectives from Lecture 15

In this lecture, we've considered how, rather than a simple astronomical curiosity, AGNs are now thought to have had a major influence of galaxy evolution. The key learning objectives are:

- Have an understanding of the indirect evidence of AGN feedback, including that derived from simulations.
- Have knowledge of the ways in which AGN might affect the evolution of the host galaxies;
- Have an understanding of the differences between jet mode and quasar mode feedback
- Have Knowledge of the direct observational evidence for radio and quasar mode feedback, and the impacts on the host galaxies.