Lecture 16:
The link between star formation and AGN activity

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1 Introduction

In the previous lecture, we saw how over the past two decades our perception of AGNs moved from them being regarded as an "astronomical curiosity" to playing a key role in regulating the growth of galaxies. The main way in which this regulation is achieved is through AGNs affecting star-formation in their host galaxies. In this lecture, we'll take a closer look at the connection between star formation and AGNs.

2 Star formation in AGN hosts

As we have seen previously, AGNs are the result of interstellar material (i.e., gas and dust) falling into the supermassive black holes that reside at the centers of galaxies. As well as producing large amounts of energy, the other direct effect of this accretion is that the black holes get more massive. As such, the mass of a supermassive black hole is the sum of all its accretion events to date.

We have also already seen that the mass of a supermassive black hole is tightly correlated with the (stellar) mass of its host bulge. However, we still don't fully understand what has caused this relationship (aside from the somewhat ambiguous catch-all term of "AGN feedback"). To try to address this, astronomers have spent a lot of time considering the star-forming properties of AGN hosts. The justification being that since galaxy bulges are formed from stars, which are produced in episodes of star formation, and black hole mass is built-up during episodes of AGN activity, then there should be some kind of link between star-formation and AGN. By studying the star-forming properties of AGN hosts, we are measuring the concurrent build-up of black hole and stellar mass.

2.1 Measuring the build-up of black hole mass

As we saw in Lecture 12, it's fairly straightforward to measure the growth rates of black holes during an accretion phase (i.e., AGN). This is because the energy radiated by the accretion process is directly proportional to the accretion rate of the black hole:

$$L_{\rm AGN} = \eta \dot{M}_{\rm BH} c^2 \tag{1}$$

so all we need to do is measure the luminosity of an AGN which can then be converted into a black hole growth rate. This is, of course, complicated by the fact we can't measure the total *bolometric* luminosity of an AGN; instead, we usually measure it in one or two bands (e.g., X-rays, optical, UV). To overcome this problem, however, astronomers measure the luminosity measured in one part of the electromagnetic spectrum and multiply it by a *bolometric conversion factors* to give an approximate bolometric luminosity.

2.2 Measuring the build-up of stellar mass in AGNs

As we saw in Lecture 4, there are a number of different ways to measure the star formation rates of galaxies. All these techniques rely on measuring the numbers of hot, young stars in a galaxy (i.e., UV continuum, Hα, infrared emission). However, in the case of measuring the star-forming properties of AGNs, it's difficult to use either the UV or Hα since AGNs contribute significantly to this type of emission. Instead, the far-infrared is widely used to measure the star-forming properties of AGNs, since AGNs are not thought to emit strongly in this part of the spectrum.

3 Non-AGNs: Main Sequence and Starbursting galaxies

Prior to considering the star-forming properties of AGN host galaxies, we should first consider what our baseline is. In other words, we need to know what the star-forming properties of non-AGNs are before we can assess whether AGNs show any systematic differences in terms of their star-forming properties.

It turns out that, at a given stellar mass, the galaxy population is bi-modal in terms of its star-forming properties: there are so-called "star-forming" galaxies and "quiescent" galaxies. These form two very distinct populations in terms of their optical colours, with star-forming galaxies being blue, and quiescent galaxies being red (due to the dominating population of old stars, not due to dust). Curiously, there are relatively few galaxies with intermediate green colours. As such, when we plot galaxy colours as a histogram, the population forms two peaks – one blue peak, and one red peak – with a "green valley" in between (yes, it is actually known as the green valley).

An important feature of the star-forming galaxy population is that the *rate* at which they form stars is tightly correlated with the mass of the host galaxy (at least for $> 95\%$ of the star-forming population). This correlation has become known as the galaxy "Main Sequence" (MS). The remaining $\sim 5\%$ of *star-forming* galaxies have star-formation rates that are *above* that of MS galaxies and are consequently known as "Starburst" (SB) galaxies. Starbursts typically have SFRs three or more times higher than MS galaxies of the same mass.

When astronomers measured the star-forming properties of MS galaxies out to higher and higher redshifts, they found that the SFR of a galaxy of a given stellar mass (which can also be express as the SFR per unit stellar mass, or specific SFR [sSFR]) *increases* with redshift. So, a typical MS galaxy at redshift 2 has a sSFR about 10 times higher than a typical Main Sequence galaxy today. At first, it was suspected that this rising SFR of MS galaxies was due to an increase in the occurance of gas-rich major mergers at earlier times, since mergers are a key means of enhancing star-formation in today's galaxies.

On more detailed morphological inspection, however, it turned out that MS galaxies at high redshifts were *not* dominated by merging systems. Instead, SBs tends to be associated with mergers at all probed redshifts, whereas MS are typically undergoing "secular" (i.e., isolated) evolution. Since MS galaxies *dominate* the numbers of star-forming galaxies at all redshifts, it therefore seems that the dominant mode of star-formation in the Universe is *not* triggered by major galaxies mergers.

If not major mergers, what *is* causing the rapid rise in the sSFRs of MS galaxies? It transpires that MS galaxies at high redshifts have significantly higher gas contents compared to their low redshift counterparts. Because of this, it is thought that the reason they are forming stars so rapidly at high redshifts is simply due to a far more abundant supply of gas in the early Universe compared to today.

3.1 Key points to remember about MS and SBs

Main-sequence and starbursting galaxies are a key feature of our current understanding of galaxy evolution, so I wanted to provide a quick summary of their properties:

- At a given redshift, galaxies on the Main Sequence (MS) have star-formation rates (SFRs) that are proportional to their stellar mass.
- So, at a given redshift, their specific SFRs (sSFR = SFR/stellar mass) is constant (but with some scatter).
- Galaxies with sSFRs $\sim 3\times$ above the MS are known as Starbursts (SBs).
- Star-formation in MS galaxies is thought to be triggered in isolation by "secular" processes, whereas in SBs it is triggered by major mergers.
- But, SBs are comparatively rare, so MS galaxies dominate the star-formation budget.
- The average (or typical) sSFR of MS galaxies increases strongly with redshift.
- This redshift evolution is thought to be due to the greater availability of cold gas in the early Universe from which to form stars.

4 AGN and the Main Sequence

Now that we have characterised the star-forming properties of normal (i.e., non-AGN) galaxies, we can consider where AGNs fit within this picture. Do AGNs predominantly live in starburst galaxies, which would suggest they are also triggered by major mergers, or quiescent galaxies (which may suggest they are "switching-off" star-formation via AGN feedback). Actually, it turns out that most AGNs reside in Main Sequence galaxies, suggesting that most AGNs are also triggered via so-called "secular processes".

You may feel that the finding that AGN preferentially reside in MS galaxies is somewhat contradictory to what we saw in Lecture 14, in which AGNs were linked to merger events. It should be noted, however, that the vast majority of AGNs in the Universe have relatively modest luminosities, whereas the merger-triggered AGNs we considered in Lecture 14 are among the most luminous AGNs in the local Universe. As such, this result reinforces thet idea that the dominant population of moderate luminosity AGNs are triggered by secular processes, but the most luminous AGNs are triggered by major mergers.

Since AGNs seem to prefer star-forming galaxies, then it makes sense to ask: "Is the luminosity of an AGN (i.e., its BH growth rate) in any way related to the star formation rate of its host galaxy?". In other words, is there a correlation between galaxy BH growth rates and star-formation rate? To investigate this, AGN astronomers have measured the average SFRs of AGN host galaxies binned in terms of the luminosity of the AGN. However, this experiment revealed little or no correlation between a galaxy's SFR and the current luminosity of its AGN. Interestingly, when we instead calculate the average AGN luminosity of galaxies binned in terms of their SFR (i.e, averaging the other way round), however, then a strong correlated between SFR and AGN luminosity *is* uncovered. In other words, when we average one way, we find no correlation, but when we average the other way, we do reveal a correlation. What's going on??

It is thought that the answer may lie in a key property of AGNs: that they vary (stochastically) on timescales that are much shorter than typical episodes of star formation. What this means is that an AGN will vary in luminosity by many orders of magnitude whilst the SFR of its host galaxy stays relatively constant. By grouping galaxies in terms of their AGN luminosity, we're selecting galaxies based on a highly stochastoc process. The effect of this is that it "dilutes" any underlying connection between the AGN and the host galaxy. By contrast, selecting galaxies based on the far more stable property of star-formation then *averaging over* the stochastic AGN variability, uncovers the true underlying links between AGNs and star-formation.

5 The probability of AGNs

As with any stochastic process, it is becoming increasingly common to think in terms of what processes affect the *probability* a galaxy hosting an AGN. For example, are AGNs more *likely* to reside in star-forming galaxies or – even better – how does the SFR of a galaxy affect the likelihood of it hosting an AGN of a given luminosity?

By thinking in such terms, AGN astronomers have begun to identify some important features of AGNs. Notably, it seems that the mass of a galaxy has no effect on whether it hosts an AGN of a given accretion rate. By contrast, recent studies have found that the likelihood of *rapid* black hole growth is enhanced in galaxies with high SFRs. As such, it seems that there may well be an underlying correlation between black hole growth and star-formation, but that uncovering this link in the face of AGN variability is going to take a lot more effort.

6 Learning objectives from Lecture 16

We've covered some quite conceptuallly-advanced ideas in this lecture, so there isn't as much reading to do as usual. I wanted to make sure there was enough time during the lecture to really explain some of the key concepts. So, don't worry too much if some of the ideas in these notes are tricky to grasp, there'll be plenty of opportunity for further explanations in the lecture. The key objectives you should take from this lecture are:

- Understand the evidence to support a connection between AGN and star-formation, i.e,;
  - BH-bulge relationship.
- Understand how we measure the AGN-SF connection, i.e.,
  - $L_{\rm AGN}$ (X-rays, etc), SFR (Optical, UV, and particularly IR etc.)
- Know what the star-forming Main Sequence is:
  - sSFR rises with redshift due to the increased availability of gas in the early Universe.
- Understand the importance of AGN variability in hampering our ability to connect AGN luminosities to other galaxy properties:

- Washes out the underlying connections

- Be aware of our current understanding of the AGN-SF connection:
  - it seems rapid BH growth is more prevalent in star-forming galaxies.