Lecture 14:
The triggering of AGN

Dr. James Mullaney

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1 Introduction

In the previous few lectures, we've seen that two ingredients are needed to produce an AGN: a supermassive black hole and supply of gas and dust to accrete onto it. In the last lecture, we considered current theories on where the supermassive black holes originate from. Now, we will consider the other major challenge in AGN astronomy: what causes the gas and dust to accrete onto a supermassive black hole to produce an AGN.

2 Dormant and active black holes

It has already been highlighted in previous lectures that it is thought that most, if not all, massive (i.e., $\gtrsim 10^9\ M_\odot$) galaxies contain a supermassive black hole at their centres (see the Solan Argument of Lecture 12). Further support of this is the clear evidence of the supermassive black hole at the centre of the Milky Way (known as Sagittarius A$*$), which clearly demonstrates that normal (i.e., non-AGNs) galaxies contain dormant supermassive black holes. These dormant black holes may "flare up" once in a while as they consume small amounts of gas and dust, but never normally enough to warrant being labelled as an AGN.[1]

In order to become an AGN, the supermassive black hole needs to accrete at a rate of at least a few percent of a solar mass per year. This material forms an accretion disk which is of the order 0.01 pc in size, but to reach these small scales the gas must lose $>>$ 99% of its angular momentum, which is no mean feat. How this is achieved is known as the "AGN triggering problem", since the transport of gas to the nucleus is needed to "trigger" an AGN, and is the focus of much research in AGN astronomy.

3 Suggested AGN triggering mechanisms

Since their discovery, a number of different mechanisms have been suggested as possible means of transporting gas from galaxy-scales (i.e., $\sim$kpc) to accretion disk-scales (i.e., sub-pc) in order to trigger an AGN. The most popular of these are:

[1] I once attended a conference presentation in which it was said that Sagittarius A$*$'s flares correspond to it accreting roughly a mountain's worth of gas within a few hours. Pretty impressive, but far from the $\sim$solar mass per year needed to power a quasar.

- **Galaxy mergers and interactions**: Because of the disruption of a galaxy's internal dynamics caused by a merger (i.e., from rotational support to a much more chaotic system) or even an "interaction" (i.e., a close fly-by leading to tidal streams), they are an extremely effective means of removing angular momentum from internal gas. As such, mergers have long been suggested as a possible means of triggering an AGN.
- **Secular processes**: The opposite of galaxy mergers/interactions are called "secular processes", and refer to when a galaxy is just going about its usual business in isolation. Suggested secular accretion mechanisms include: spiral arms or bars channelling gas to the nuclear regions, the accretion of small satellite galaxies (i.e., those that form the tidal streams around the Milky Way and are too minor to be considered true mergers), winds or ejecta from processes associated with star-formation (including supernovae). Basically anything *internal* that could channel cold gas in the galaxy toward the nuclear regions.
- **Accretion of hot halo gas**: All galaxies sit within a dark matter halo. These halos contain large amounts of very diffuse gas (indeed, the majority of gas in the Universe is in this state) believed to be kept hot ($\sim 10^6$ K) by feedback mechanisms (i.e., energy injected from the galaxy, not least by AGN) and shock heating. It has been suggested that some of this gas can penetrate to the centre of a galaxy and by accreted in a "hot mode" to via Bondi accretion (in which the gas does not form an accretion disk; feel free to look it up, but we won't go into more details here). Alternatively, some of this hot gas may cool (to $\sim 10^4$ to 10^5 K) to form what are known as "cooling flows" which stream onto the galaxy (toward the centre of mass) from the halo.
- **Cold accretion from large-scale filaments**: Some galaxies (especially massive ellipticals) live at the nodes of large-scale (i.e., many tens of Mpc) filamentary gaseous structures. These structures are very effective at transporting gas toward the nodes where the galaxies sit, and it has been suggested that they may even penetrate the galaxies right to their nuclei. If that is the case, they may provide a direct channel to feed an AGN.

For the rest of the lecture, we'll consider if there is any evidence for these various potential mechanisms (we'll bunch the final two together, as they are essentially the same thing - accreting material from scales far larger than the galaxy).

4 Galaxy mergers and interactions

Perhaps the easiest triggering mechanism to test for is mergers or interactions. If we find a significantly higher proportion of AGNs in galaxies that are undergoing mergers compared to non-AGNs, then we can infer that the merger process is, indeed, an effective means of funnelling gas toward the galaxy nucleus to trigger an AGN. Note, however, the importance of a comparison sample in that statement: it is crucial that we compare like-for-like AGN and non-AGN galaxies when trying to identify AGN triggering mechanisms. This typically involves identifying a mass-matched sample of non-AGNs which, thankfully, is usually comparatively straightforward since non-AGNs outnumber AGNs by many tens-to-one.

To date, a number of studies have explored the question of whether AGNs preferentially reside in merging systems. Because of the difficulty in spanning very broad ranges of AGN luminosity in our samples (recall the lecture on extragalactic surveys, in which we saw that different depths and areas of surveys were used to identify different luminosity systems), these studies typically focus on a comparatively narrow luminosity range. Results from deep-field surveys in particular show no evidence of a higher fraction of mergers among moderate luminosity AGNs (i.e., $L_{\rm Bol} \lesssim 5 \times 10^{44}$ erg s^{-1}) compared to non-AGNs in the same fields. This suggests that secular processes of the type highlighted in the previous section are triggering these lower luminosity AGNs.

The triggering mechanism for more luminous quasars may, however, differ from more moderate, less luminous AGNs. This may well be because more violent processes are needed to channel the greater amounts of gas needed to trigger quasars than can be achieved with sedate, secular processes. Indeed, computer simulations predict that the peak of AGN activity (which we would observe as a quasar) take place during the final stages of a major galaxy merger. To test this, however, requires a sample of powerful quasars with sufficient quality observations to see signs of recent merger activity.

4.1 The 2Jy sample of radio galaxies

Among the most well-studied samples of nearby (i.e., $z < 0.7$) luminous AGNs is the 2Jy sample of southern radio galaxies (a radio galaxy is another name for a radio loud AGN). Although originally selected because of their high radio luminosities (they all have radio fluxes above 2 Jy, which makes them some of the brightest radio sources in the whole sky), it turns out that almost 80% of the AGNs in the 2Jy sample are also optically-luminous quasars (although in some cases, the nucleus is obscured from view; see the lecture 11 on AGN unification).

Using very deep (i.e., sensitive) optical imaging for the 2Jy sample, astronomers have found that around 15% show evidence of undergoing current major mergers. Furthermore, a further 70% of them show clear evidence of tidal features, which are a tell-tale sign of recent galaxy interactions. This is a much higher fraction than found in matched comparison samples of non-AGNs in the local Universe. This is consistent with the idea that powerful radio galaxies (and possibly most quasars) are triggered in galaxy interactions. However, contrary to what is suggested by simulations, it seems that the triggering isn't associated with a particular stage of a merger, simply that a merger has taken place in the recent past (within a few 100 Myr; i.e., a late-stage merger).

5 The role of star-formation

One of the main problems with trying to figure out what triggers AGN is that, invariably, multiple *potential* triggering mechanisms are present in a galaxy *at the same time*. In particular, major gas rich mergers also induce high levels of star formation within galaxies (due to the compression of cold gas clouds within the colliding galaxies). It can, therefore, be difficult to assess whether the AGN is, indeed, triggered by the merger, or whether it's really the star-formation that induces the AGN and the merger's role is simply to enhance the levels of star-formation. While this may be a moot point for mergers (after all, it's ultimately the merger which triggers AGN), but it's important for AGN triggering in general to know whether star-formation (which is common) is sufficient, or whether some kind of interaction (which is rare) is critical to trigger an AGN.

Trying to untangle the role of star-formation vs. merger is further complicated by the difficulties in measuring accurate rates of star formation in galaxies hosting powerful AGNs. This is because a powerful AGN can contribute to all of the wavebands traditionally used to measure star formation rates (SFRs). For example, a bright Type 1 AGN will dominate over any star formation at UV wavelengths, and even a Type 2 AGN can contribute to the UV bands via reflected light (reflected from clouds of gas within the galaxy). Similarly, while AGNs are typically quite weak at far-infrared wavelengths, even here they can dominate over low levels of star-formation (to add a further complication: the intrinsic SED of AGNs remains poorly constrained at infrared wavelengths).

Perhaps the most reliable means of measuring the SFRs and star-forming histories of *powerful* AGNs is via sensitive spectroscopy observations of the host galaxies. Stellar absorption features in the spectra can be modelled (via spectral synthesis) to give precise ages of the stellar populations in the host galaxy, and by placing the slit off-nucleus, the emission from the AGN itself can be mitigated. When this is done for the 2Jy sample of nearby bright quasars, young stellar populations are only detected in about 20-35% of the sample. This has been interpreted as evidence that, while interactions may play a key role in triggering AGNs, in most cases they are not triggered at the *peak* of major, gas rich mergers when most of the star-formation takes place. This has led some to speculate that there is a *delay* between the closest approach of a merger and the triggering of an AGN.

6 Triggering via cool gas accretion

The final suggested means of AGN triggering we will consider is via direct accretion of cold gas from intergalactic space (via cooling flows or channelled along large-scale filaments). In order to power a quasar with a bolometric luminosity of $L_{\rm Bol} > 10^{45}$ erg s^{-1}, a black hole must accrete at a rate of roughly 0.2 M$_\odot$ yr^{-1}. If a typical quasar lifetime is of the order 10^6 to 10^8 years (the former based on the size of the largest radio jets, the latter based on the fraction of massive galaxies hosting quasars within a given redshift range [i.e., within a given time interval]), then this means that the black hole will accrete roughly $2\times10^5 - 2\times10^7$ M$_\odot$ of gas during a typical quasar episode.

However, that only represents the gas that falls into the black hole, yet the black hole-to-bulge mass relationship tells us that for every one solar mass of gas/dust that falls into the black hole, there must be 500 M$_\odot$ that forms stars. As such, to fuel a quasar for about 10^6 to 10^8 years requires a *total* gas reservoir of $10^8 - 10^{10}$ M$_\odot$ (and that's assuming a 100% efficiency in converting gas into stars, which is far from the case in reality). So, the key question is: "Is there any evidence that such a large gas reservoir is even available to fuel a quasar?".

In astronomy, measuring the mass of gas contained within a given region is notoriously difficult. If the gas is ionised, we can use the strength of ionisation lines as a proxy-measure. However, the ionised phase only represents a small fraction of gas in a galaxy available to form stars or accrete onto a black hole. Instead, the dominant gas supply is either in the neutral or molecular phase, which doesn't emit at optical wavelengths. It is possible to use the Hydrogen 21 cm line in the radio bands, but this is weak and so only detectable in the most nearby galaxies. So, to measure the amount of neutral gas available, astronomers use the fact it is often accompanied by large amounts of dust, and so use the dust mass as a proxy for gas mass (a ratio of $M_{\rm Gas}/M_{\rm Dust} \sim 100$ is typically assumed). Since dust emits as a black body, if we know its temperature (which we can calculate using infrared colours), then we can calculate its mass from its (infrared) luminosity.

If quasars are being fuelled by cold gas within their host galaxies, then we should measure dust masses of around $10^6 - 10^8$ M$_\odot$ (i.e., around 1% of the required gas mass) in galaxies hosting powerful quasars. Using the *Herschel* infrared telescope, which was launched in 2009, astronomers have measured the infrared temperatures and luminosities (and consequently, masses) of the dust around powerful quasars, including the 2Jy sample. As predicted, they do indeed contain typical dust masses of around 10^7 M$_\odot$, confirming that there is sufficient gas to fuel their resident quasars for $\gtrsim 10^6$ years.

Finally, to give you some sense of how large 10^8 $M_\odot$ of gas is, the Large Magellanic Cloud (LMC) contains roughly this amount of gas. So it is feasible that, should the Milky Way eventually merge with the LMC (which would be classed as a minor merger), there would be sufficient gas supplied by the interaction to trigger Sagittarius A$*$ into becoming a quasar.

7 A summary of AGN triggering mechanisms

Over the course of this lecture, we have seen how various different mechanisms have been suggested as possible means of triggering an AGN. As you have probably already noted, there is no "single -fix" to this issue, with mergers/interactions, secular processes and cool accretion all possible mechanisms (we'll also consider evidence that star-formation may also be linked to AGN in Lecture 16). However, this probably shouldn't be too much of a surprise; all it takes to power an AGN is material falling onto a black hole. The black hole doesn't care how the material is funnelled onto it, so it's probably to be expected that different triggering processes can all play a role.

I feel the key thing to take away, however, is that there seems to be evidence that AGNs of different luminosities seem to be triggered by different processes. For more moderate luminosity AGNs, it seems that secular processes are sufficient (including, as we'll see in L16, non-merger-induced star-formation). By contrast, there is increasing evidence that the most luminous AGNs are, indeed, triggered (or at least, helped) by a galaxy merger/interaction. One thing I can tell you for *for certain* is that this is a highly active area of current research (so nothing is really certain!), so our understanding of AGN triggering may change considerably over the coming years.

8 Learning objectives for Lecture 14

In this lecture we've considered the possible mechanisms of driving gas and dust from the outskirts of a galaxy toward its nuclear regions in order to trigger an AGN. This is a highly active area of research and, consequently, remained surrounded in uncertainties. Having said that, there are some key things you should take from this lecture(!):

- It appears that moderate luminosity AGNs are triggered by "secular" processes.
- Local radio galaxies (i.e., the 2Jy sample) are diverse in terms of their detailed morphologies, star formation properties, and cool ISM contents.
- A small but significant minority ($\sim$15%) are triggered in major, gas-rich mergers in which both the super-massive black holes and stellar masses of the host galaxies are growing rapidly.
- But the majority of local radio galaxies represent much later stages of galaxy interaction, possibly indicating a late-time re-triggering of AGN activity via galaxy interactions and/or minor mergers (2xLMC gas mass)