Lecture 11:
AGN discovery and observed properties

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1 Introduction

Up to this point in the course we have considered "normal" galaxies whose light is produced exclusively by stars. There is, however, a class of galaxy in which a significant proportion of the total energy output is being emitted instead by material falling into a central supermassive black hole. Because of the extreme amounts of light being produced at their centres, these are known as "Active Galactic Nuclei" (AGN) and are currently thought to have had a major influence on how today's galaxies have formed and evolved. In this lecture, we'll cover how AGNs were first discovered and discuss their main properties.

2 The discovery of AGN

The earliest known account of the study of an AGN is that of Fath in 1908, in which he obtained the spectra of a number of "spiral nebulae" (this was before Hubble had demonstrated that such nebulae were, indeed, galaxies external to our own). Fath noted that while most of the spiral nebulae in his sample displayed spectra consistent with a population of unresolved stars, one – NGC 1068 – had a "composite spectrum, showing both bright [emission] and absorption lines". In the years that followed, a few other observers noted the peculiar "planetary nebulae-like" spectra of some other spiral galaxies (notably NGC 4051 and NGC 4151), but little more was made of these somewhat rare systems.

It wasn't until 1943 that AGNs were studied in any kind of systematic way. At this time, Carl Seyfert obtained the spectra of six nearby galaxies that all showed evidence of a bright, stellar-like nucleus. Seyfert noted that all of these galaxies showed evidence of strong emission lines superimposed on an otherwise normal galaxy spectrum. Most interestingly, however, was that in some cases (e.g., NGC 3516, NGC 7469), the permitted Hydrogen emission lines (i.e., Hα and Hβ were extremely broad (i.e., they covered a wide range of wavelengths). Seyfert attrbuted these broad lines to Doppler shifts, corresponding to velocities of up to 8,500 kms^{-1}. By contrast, in other cases (e.g., NGC 1068) the permitted Hydrogen emission lines had similar widths as the comparatively narrow (corresponding to up to $\sim$ 3000 kms^{-1}) forbidden emission lines. [1] As we shall see, the differences in the widths of the permitted emission lines continue to be used today to group AGNs into two different types:

[1]Unfortunately, Carl Seyfert died in a car accident before his important work on AGN was fully appreciated. He did, however, present the daily weather bulletin the local news whilst employed as full-time astronomy professor in Tenessee, which makes him awesome.

- Type 1 AGNs: Display broad (> 2000 km s^{-1}) permitted emission lines (e.g., Hα, Hβ), but narrow (typically < 1000 km s^{-1}) forbidden (e.g., [O III], [N II]) emission lines in their optical spectra.

- Type 2 AGNs: Display permitted and forbidden emission lines with roughly the same comparatively narrow (typically < 1000 km s^{-1}) widths.

In addition to differences in their emission lines, Type 1 and Type 2 AGNs also tend to have different continuum features. Type 1 AGNs typically have very blue continua that are quite devoid of absorption lines. Type 2 AGNs, by contrast, have much redder continua which display evidence of stellar absorption features. Indeed, the spectra of Type 2 AGNs typically look like those of normal galaxies, but with strong narrow permitted and forbidden emission lines.

3 AGN in the radio era

While Seyfert's work is now widely regarded as as groundbreaking in terms of the first systematic study of AGNs, it was largely ignored by other astronomers at the time. In fact, it took until the development of radio astronomy before AGNs would start to more widely studied by astronomers.

During the Second World War there was a lot of research conducted in the areas of radio communication and radar. Once the war ended, some of the engineers and scientists that had worked on radio communications during the war turned their attention to trying to determine where the persistant background "noise" that was picked up by their receivers came from. While it was soon realised that a significant fraction of radio noise came from the Sun, there remained significant "noise" from other non-terrestrial sources. The problem, however, was that the angular resolution of early radio telescopes was extremely poor (i.e., many degrees on the sky), making it very hard to pinpoint the positions of the radio sources to better than a few tens of degrees. With this level of resolution, radio astronomers were only able to locate a bright sources to be within an entire constellation, so the first radio sources were referred to by the constellation in which they were detected (e.g., Cygnus, Cassiopeia).

By the mid 1940s, radio astronomy technology had developed sufficiently to begin to pinpoint the positions of radio sources beyond the solar system. This was enabled by the development of radio interferometry techniques, the first of which exploited the "sea-cliff" technique. This involved situating a radio reciever at the edge of a sea-facing cliff. As the radio source rose above the horizon, some of its radio waves would travel directly toward the receiver, while others would be reflected off the surface of the sea before reaching the receiver. This effectively creates two radio sources that interfere with each other, creating a radio interference pattern. The end result is an interferometer with a baseline twice the height of the cliff, greatly increasing the angular resolution of the telescope without the need for connecting cables and correlators between two separate receivers.

Using this technique, early radio astronomers began to be able to pinpoint the position of bright radio sources on the sky. This revealed that the very bright source in Cygnus previously detected in low-resolution studies was compact, extending less than 8 arcminutes on the sky. With such levels of angular precision, by 1949 astronomers were able to associate the radio sources with those detected at optical wavelengths. In doing so, it transpired that Cygnus A was, in fact, associated with galaxy merger at a distance of 252 Mpc, meaning it has a total radio luminosity of $> 10^{45}$ ergs s^{-1} – more than the luminosity of all the stars in the merging galaxies combined. With the ratio of radio to optical luminosity of Cygnus A so much higher than that of a star, it must mean that the radio emission must be coming from another type of source. Later, in the 1960s, it was realised that this alternative source of radio energy was associated with galaxies showing optical properties the same as those reported by Seyfert around 20 years earlier - i.e., AGNs.

4 AGN classification

With the realisation that many of the brightest radio sources in the sky were associated with AGNs, interest in these objects increased dramatically. However, with some of Seyfert's original optical AGNs *not* associated with bright radio sources, it was soon appreciated that not all AGNs were powerful radio emitters. Instead, it seemed that in addition to the Type 1/Type 2 classification, there should also be a radio "loud" and radio "quiet" distinction.[2] Further, both radio loud and radio quiet AGNs can either be Type 1 or Type 2 AGNs; in other words, there is no obvious connection between an AGN's optical classification and its radio classification. So, there are:

- Radio loud:
  - Type 1: Broad Line Radio Galaxy
  - Type 2: Narrow Line Radio Galaxy
- Radio quiet:
  - Type 1: Seyfert 1
  - Type 2: Seyfert 2

Added to this, however, is another completely arbitrary distinction based on the *optical luminosity* of AGNs, with the most optically luminous AGNs known as *Quasars*. This unfortunate situation has arisen because quasars are so bright that when they were first discovered, their host galaxies could not be seen due to the "glare" of the light from the AGN. Indeed, they looked like very bright stars but with peculiar spectra (hence their name, which refers to "quasi-stellar objects"). As a consequence, their connection to Seyfert AGNs (which are all in easily-seen galaxies) was not realised at first, and by the time it was, the name had stuck. So, now we have:

- Radio loud:
  - Type 1:
    - High optical luminosity: Radio Loud Quasar
    - Low optical luminosity: Broad Line Radio Galaxy
  - Type 2:
    - High optical luminosity: Radio Loud Type 2 Quasar
    - Low optical luminosity: Narrow Line Radio Galaxy
- Radio quiet:
  - Type 1:

[2] "Loud" and "Quiet" typically refer to the ratio of radio luminosity to optical luminosity of an AGN, rather than the absolute radio luminosity. Despite being adjectives of sound volume, this is referred to as a measure of the radio *loudness* of a source, rather than its radio "volume" (since the latter has a double meaning in physics).

    * High optical luminosity: Radio Quiet Quasar
    * Low optical luminosity: Seyfert 1
  - Type 2:
    * High optical luminosity: Radio Quiet Type 2 Quasar
    * Low optical luminosity: Seyfert 2

What a nightmare!

5 AGN Unification

As the tale of the discovery of quasars indicates, as the different types of AGNs were being discovered, it wasn't at all clear to astronomers that they were, indeed, the same type of object. Are, for example, Type 1 AGNs completely distinct from Type 2 AGNs, or are they somehow manifestations of the same object?

The anwer to this specific question came in the mid 1980s as a result of the study of Type 2 AGNs in polarised light. When light is reflected, it becomes polarised, so when it was discovered that Type 2 AGNs showed evidence of Type 1-like broad emission lines in their optical spectra, it was interpreted that what was being detected was the reflected light from an otherwise "hidden" region. This led to the suggestion that the region responsible for the broad lines in Type 1 AGNs – i.e., the *broad line region* (BLR) – was indeed present in Type 2 AGNs, but was simply hidden from our view. However, the obscuring material could not be blocking *all* the light from this BLR, since some of it was being observed in polarised light. The interpretation was that surrounding the BLR of *all* AGNs is a "torus" of obscuring dust; in the case of Type 1 AGNs, we're looking down the hole of the torus, directly at the BLR, whereas in the case of Type 2 AGNs, the torus is side-on and thus blocks our line-of-sight to the BLR.

Today, this "dusty torus" is a major component of the "Unified AGN model", which explains the observed properties of AGNs in terms of a specific geometry:

- At the very centre of an AGN is a supermassive black hole.
- Surrounding the supermassive black hole is an accretion disk formed from gas and dust sprilling toward the black hole. As this material falls toward the black hole, it travels faster and increases in temperature due to friction. As it heats up, it radiates this heat in the form of light, sometimes outshining its entire host galaxy (as is the case of quasars).
- Slightly further out from the accretion disk is the BLR. The BLR consists of clouds of gas that are being illuminated and ionised by the light from the accretion disk. Being close to the black hole, they orbit it at high velocities, hence the emission lines they produce are strongly doppler broadened. The are also dense, and so only emit permitted emission lines.
- Surrounding the accretion disk and BLR is the dusty torus which, in the case of Type 2 AGNs, blocks out the light from *both* the accretion disk and the BLR.
- Beyond the dusty torus is the so-called *narrow-line region* (NLR). This is simply ambient gas in the host galaxy that is being illuminated and ionised by the AGN. This gas is far more rarified than that in the dense BLR, and hence emits in both permitted and forbidden emission lines. Since it is larger than the dusty torus, we observe emission from the NLR in both Type 1 and Type 2 AGNs.

Within the unified model, Type 1 and Type 2 AGNs are manifestations of *the same* object. The reason for their different appearances is simply due to the orientation of the dusty torus relative to our line of sight.

6 The multiwavelength continua of AGNs

An important consequence of the structure of an AGN is that they can emit strongly at almost all observable wavelengths, with each component of the unified model emitting at different wavelengths. With its high temperatures, the accretion disk emits strongly at optical through to ultraviolet wavelengths which can be seen directly in the case of Type 1 AGNs. Furthermore, some of the gas surrounding the accretion disk is heated to millions of degrees, which upscatters ultraviolet photons to X-ray energies. As such, AGNs are the strongest sources of X-rays in the Universe. Further out, the dusty torus is heated by light from the accretion disk which is then re-radiated at infrared wavelengths. At even longer wavelengths, in radio-loud AGNs, magnetically entrained jets propogate from the central regions of the accretion disk, emitting powerful synchrotron radiation as they do so.

7 AGN identification

Since AGNs are strong emitters of light spanning almost the whole observable electromagnetic spectrum, many different techniques emploiting different wavelengths of light have been developed to identify AGNs among "normal" galaxies. In this section, we'll consider some of the most commonly used approaches to identify AGNs. It is important to note, however, that the various techniques come with their own biases; for example, some are only sensitive to a particular type of AGN (e.g., optical Type 1 or Type 2), whereas others will only identify particularly luminous AGNs.

7.1 Optical selection

With Type 1 AGNs displaying strong blue optical continua, we can use this property to identify AGNs using broad band optical photometry (i.e., using imaging taken with different filters). Basically, what astronomers do is search for point like sources with blue rest-frame optical colours. Of course, this has to be able to account for K-correction, so different combinations of filters are used to identify the blue continua indicative of quasars at different redshifts. However, the AGN continuum must dominate strongly over the continuum of the rest of the galaxy for this selection to work. As such, this technique is biased in favour of the most optically luminous AGNs whose light dominates ovet the host galaxy. Of course, it only also only applies to finding Type 1 AGNs, since the blue optical continuum from the accretion disk is blocked by the torus in Type 2 AGNs.

7.2 Radio selection

This is an easy one. Roughly 10% of all AGNs are radio loud, so we can use radio surveys to identify them. However, since AGNs are not the only astronomical sources that produce radio emission we need to be careful to account for other types of sources that could contaminate our radio sample. The biggest type of contaminant are star-forming galaxies (since star-formation is accompanied by supernovae, whose remnants are strong radio emitters) and supernovae remnants in the Milky Way. However, almost every source with radio luminosities greater than 10^{23} W Hz is a radio loud AGN, so it is fairly easy to exclude contaminants via a radio luminosity cut. However, this does mean that radio selection is biased toward radio luminous AGNs (since AGNs with low radio luminosities will be thrown out with the star-forming galaxies). Since radio wavelengths are immune to dust obscuration, radio selection picks out both type 1 and type 2 radio AGNs.

7.3 Infrared selection

Being exposed to lots of high energy photons from the accretion disk, the dust surrounding the AGN gets very warm (indeed, the dust nearest the accretion disk gets so hot it actually evaporates). As such, AGNs are strong sources of infrared emission and have characteristic infrared colours. We can therefore use infrared colour selection to identify AGNs. However, as we have seen, low mass stars and star-formation can also produce a lot of near and mid infrared emission, respectively, so the emission from the AGN must dominate over the emission from the host galaxy in order for it to be identified via infrared selection. As such, infrared selection is biased in favour of AGNs above a certain AGN luminosity to galaxy mass, or AGN luminosity to SFR ratio. However, since infrared is relatively impervious to dust, infrared selection identifies both Type 1 and Type 2 AGNs.

7.4 Emission line selection

The accretion disk at the centre of an AGN – the "central engine" – produces large amounts of high ionising UV photons. Moreso even than the hottest, most massive stars. This intense UV flux is capable of ionising gas in the narrow line region to very high levels – emission lines from species with five or six missing electrons are not uncommon in the spectra of AGNs. This means that AGN spectra contain strong emission lines from highly ionised species, such as [O III]. Because the relative strengths of different emission lines in AGN spectra differ from those of non-AGNs, we can use emission line ratios to identify AGNs. The most commonly used emission line ratios are [O III]/Hβ and [N II]/Hα, with AGNs having high values of each of these ratios compared to non-AGN galaxies. Since each pair of emission lines are close to each other in wavelength (i.e., [O III] at 5007 Å, Hβ at 4861 Å, and [N II] at 6548 Å, Hα at 6563 Å) the effects of dust on each ratio cancels out.

As with all the AGNs selections highlighted here, however, emission line selection does have its pitfalls. Firstly, obtaining spectra is time-consuming, and only a fraction of all the galaxies in an imaging survey will have been observed spectroscopically. Further, as with all AGN selection techniques, the AGN features must dominate over any features arising from the host galaxy. This means that only AGNs with strong emission lines relative to those arising from the host galaxy will be selected by emission line selection. However, if measured carefully, emission line selection can identify both Type 1 and Type 2 AGNs.

7.5 X-ray selection

As mentioned previously, AGNs are the strongest emitters of X-rays in the known Universe, with some AGNs emitting $> 10^{46}$ ergs s^{-1} in X-rays alone. Since no other objects produce such large amounts of X-rays, X-ray observations are a relatively "clean" way of identifying AGNs. Further, since X-rays are emitted by the central regions of the accretion disk itself, they give us a very good measure of the "instantaneous" luminosity of the AGN.

The key pitfall of X-ray emission, however, is that it can be obscured by large columns of gas and dust. However, X-rays are less susceptible to absorption than the UV and the shorter wavelengths of optical light, and the highest energy photons (i.e., energies about about 10 keV) can penetrate very dense clouds of gas and dust. Since X-rays aren't totally impervious to obscuration, however, they are more likely to identify Type 1 AGNs relative to Type 2 AGNs (but like-for-like they find relatively more Type 2s than optical selection).

8 Lecture 11 learning objectives

In this lecture we took a turn away from normal galaxies to study AGNs. As we shall see, astronomers now think that AGNs have played a major role in shaping today's galaxies, so we'll explore them further for the next six lectures. For now, however, here are the learning objectives from this lecture:

- Know how AGNs were first discovered and studied at optical wavelengths during the first half of the 20th century.
- Have an appreciation of the role that radio astronomy has had in raising the interest in AGNs.
- Know the various different classes of AGNs, and understand the differences between them (especially the difference between a Type 1 and Type 2 AGN).
- Be able to describe the AGN Unified Model, and explain how it accounts for the different AGN types.
- Know the main ways we identify AGNs, and the benefits and pitfalls of each approach.