Lecture 12:
AGNs and supermassive black holes

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1 Introduction

Last lecture, we took our first look at Active Galactic Nuclei (AGNs). We learned how they were discovered, the different types of AGNs and how they are "unified", and how different parts of the electromagnetic spectrum are used to distinguish AGNs from "normal" galaxies. In this lecture, we'll consider where all the energy in an AGN comes from by taking a closer look at black hole and accretion disk system that forms the so-called "central engine".

2 Central engine characteristics

As we saw in the previous lecture, the first AGNs to be studied in any kind of detail were moderate luminosity "Seyfert-like" AGNs. While these first studies highlighted the curious observed properties of the nuclei of these galaxies, they didn't make any real attempt to explain their cause. This all changed when the distances to the first known quasars were measured and the consequent appreciation of their extreme luminosities. With the brightest known quasars having luminosities equivalent to 10,000 Milky Way-like galaxies, you can see why astronomers quickly began to question what could be the generating so much power.

Clearly, any theory to explain what powers a quasar must be able account for their extreme luminosities. However, it was soon realised that the power was not the only peculiar aspect of AGNs that any model of energy production must be able to explain. Take their optical spectra, for example. Type 1 AGNs in particular display spectra that are unlike any other type of object; no other celestial body displays emission lines with widths corresponding to thousands or even tens of thousands of km s^{-1}. What was causing such extreme velocities? In addition, any theory of energy production must be able to explain the very large radio luminosities of AGNs. Indeed, as the angular resolution of radio telescopes improved, it was discovered that the radio emission of some AGNs is being emitted by powerful radio jets that extend over many tens or even hundreds of kpc. Any model of the central engine must be able to explain what is launching such powerful jets (which, recall, can be more luminous at radio wavelengths than the *bolometric* output of all the stars in the host galaxy).

An interesting and important consequence of the discovery of *extended* radio jets was that it revealed that some AGNs had been generating power for long enough to launch jets that are millions of light-years long. Clearly this implies that some AGNs had been generating vast amounts of energy for millions of years, and were thus not the type of short "explosive" events normally associated with more familiar extreme phenomena such as supernovae. Clearly, any theory of energy production must therefore be able to explain how this energy output can be maintained for so long.

2.1 AGN variability

Of all the extreme properties of AGNs, perhaps the most puzzling – yet ultimately revealing – feature for astronomers was their rapid variability. Soon after the first discovery of quasars it was realised that their optical flux varied on timescales of a few days to years. While they always stayed extremely luminous, their brightness would change be a factor of a few within a relatively short period of time.

The reason why the rapid variability of quasars is so interesting is because how rapidly something varies reveals something about its size. For example, it would be impossible for anything as large as a whole galaxy to vary in brightness in the space of a year. This is because it takes time for the "information" regarding that change to be transmitted from one side of the galaxy to the other. The fastest any information can travel is the speed of light, so the fastest something as large as a galaxy can vary in brightest would be a few tens of thousands of years. So, if a quasar changes brightness over a period of just a few days, then it implies that its *maximum* size is a few light-days across. This means that the central engine of some AGNs is, at maximum, not much bigger than our solar system – an absolute minuscule size in galaxy terms. So, early AGN astronomers were faced with the incredible concept that more power than that emitted by all of the stars in the Milky Way is coming from a region of space not much bigger than our solar system!

3 Suggested AGN energy sources

There's an old saying that goes something like: "if the only tool you have is a hammer, you'll treat every problem as if it's a nail". Up until the middle of the 20th century, the only thing astronomers had ever known was stars and planets (galaxies are, after all, just collections of lots and lots of stars), so it was tempting to try to solve the "problem" of the AGN power source by appealing to stars. However, as we shall see, all of these theories had extreme shortcomings.

3.1 A 10^6 solar mass star

Among the first suggestions for what could be powering bright quasars was that it was a single extremely massive star. As we have seen, the most massive stars in a galaxy are very hot and are disproportionately bright for their mass (i.e., a star ten times more massive than the Sun is more than ten times more luminous). Perhaps inspired by the stellar-like appearance of quasars, some early AGN astronomers suggested that AGNs were, in fact, a single star with a mass of over a million solar masses. Such a star would, indeed, be extremely bright and would also emit strongly at ultraviolet wavelengths and could therefore explain the blue continua of AGNs. A very massive star would also satisfy the compactness requirements, and its strong gravity could be used to explain the broad emission lines through gravitational doppler broadening.

Despite accounting for some AGN properties, the massive star theory falls down on many key points. Firstly, such a massive star would be extremely short lived, possibly only lasting a few tens of thousands of years – not long enough to maintain the extended radio jets seen in some AGNs. Speaking of which, there is no known star that produces such collimated radio jets; how would a massive star do so? Further, stellar masses are known to form a continuum distribution (i.e., the initial mass function), so if there are million solar mass stars powering AGNs, where are all the slightly smaller, hundred thousand solar mass stars?

3.2 A massive star cluster

Another star-based early suggested model for the central engines of AGNs was a very dense central stellar cluster consisting of thousands or even millions of massive (i.e., > 20 M$_\odot$) stars. Being massive, these stars would quickly undergo supernovae one after another, which would explain both the high luminosity and variability of AGNs. Also, the combined radio emission of the supernovae remnants could explain the high radio luminosities of AGNs.

While it would be technically possible for this number of massive stars to be packed into a volume the size of the solar system, this model has a number or drawbacks. Firstly, it isn't clear how such a setup would create the collimated jets we see being launched from AGN. Most importantly, however, is that the spectral features of AGNs simply do not look like those of supernovae remnants

3.3 A central supermassive black hole

With all the attempts to use stars to explain the properties of AGNs looking extremely contrived (and yet still failing to explain key observed AGN features), a few theorists started to consider other non-stellar possibilities. As we now know, the most successful of these was the idea that a supermassive black hole is, ultimately, responsible for the AGN phenomena. With black holes the densest form of matter in the Universe, they are ideal candidates to meet the "compactness" requirement. However, since black holes by definition emit no light, how can they account for the most fundamental property of AGNs: their extremely high luminosities?

As we mentioned in the previous lecture, the key to an AGN's luminosity is not the black hole itself, but the accretion disk that forms around the black hole as it consumes surrounding gas and dust. As the material falls toward the black hole, it releases its gravitational potential energy in the form of light. In fact, this release of gravitational energy as material falls onto a supermassive black hole is an incredibly efficient process, with roughly 10% of the rest mass of the falling material being converted into light. This compares to $< 1\%$ efficiency for nuclear fusion in stars. Indeed, the release of energy due to gravitational collapse is the second only to matter/anti-matter annihilation in terms of its efficiency in converting rest mass into radiated energy. As such, even a relatively modest accretion rate of about one solar mass per year is sufficient to power a quasar of bolometric luminosity $\sim 5 \times 10^{45}$ erg s^{-1}.

So, an accreting supermassive black hole can explain both the power output and variability of AGNs (the latter because of its highly compact nature). But what about those radio jets seen in a subset of AGNs? Can an accreting black hole explain those as well? Well, one popular theory is that as the accreting material gets hotter and hotter, it starts to become ionised. As such, it forms a fast-moving plasma, which generates a strong magnetic field (as all moving charges do). It is thought that if the black hole is spinning, it will tangle the magnetic field lines up into a spiral pattern. Any electrons and plasma caught within this magnetic field will be accelerated to close to the speed of light, forming tightly collimated jets.

Finally, as we saw in the previous lecture, a supermassive black hole plus accretion disk system can explain the very broad emission lines seen in the spectra of Type 1 AGNs. As a reminder, these broad lines are being emitted by dense, ionised gas orbiting close to the black hole, which explains their extremely high velocities.

4 Finding evidence for supermassive black holes

While it seems that accreting supermassive black holes can explain very well many of the observed properties of AGNs, this does not constitute a proof that it is correct. For that, we would ideally identify evidence of supermassive black holes in the centres of galaxies. Before doing so, however, it would be useful to have some kind of indication of the expected masses of a supermassive black hole, just so we've got some idea of how challenging measuring them will be.

4.1 The Eddington Limit

One way of obtaining a rough lower limit for the mass of an accreting supermassive black hole is by assuming that they are accreting close to their Eddington luminosity. You should recall from previous lecture courses that the Eddington luminosity for an accreting object (whether a star or a black hole) is reached when the gravitational force pulling the material inward is balanced by the radiative force from the photons emitted by that accreted material. Equating these two forces gives:

$$L_{\rm Edd} = \frac{4\pi G M m_p c}{\sigma_T} \tag{1}$$

where G is the gravitational constant, M is the mass of the central object (in our case, a supermassive black hole), m_p is the proton mass, and σ_T is the Thompson cross-scattering area. Entering the numerical values for the constants, and converting the units gives:

$$L_{\rm Edd} = 1.3 \times 10^{38} \left(\frac{M}{\rm M_\odot}\right) \text{erg s}^{-1} \tag{2}$$

We have already seen that the brightest quasars accrete at a rate of roughly one solar mass per year, producing a bolometric luminosity of about 5×10^{45} erg s^{-1}. Plugging this luminosity into the above equation gives a black hole mass of $5 \times 10^{45}/1.3 \times 10^{38} \approx 4 \times 10^{7}$ M$_\odot$. However, this assumes the black hole is accreting at its Eddington luminosity, whereas it is likely to be accreting at a rate somewhat lower than this. As such, this gives a *lower limit* to the mass of the black hole. Clearly, this is much more massive than a conventional, stellar mass black hole (which may reach a few tens of solar masses at most).

4.2 The Soltan Argument

Another way of getting an estimate of the mass of all supermassive black holes in today's Universe is to (a) sum up all the material that has ever fallen into a supermassive black hole and (b) assume that this mass is distributed evenly among all massive galaxies. This clearly assumes that all massive galaxies contain a central supermassive black hole, and thus again represents a lower mass limit. This methodology was first proposed by Soltan in 1982, and so it referred to as the Soltan Argument.

Part (a) sounds incredibly difficult: How can we possibly measure all of the mass that's ever fallen into a supermassive black hole? In practice, however, it's relatively straightforward (given some reasonable assumptions and some careful measurements). Black holes grow by accreting material, and as we have seen, the amount of light they emit is directly proportional to their accretion rate (assuming a given accretion efficiency). This means that the AGN luminosity function (i.e., the histogram of AGN luminosities per unit volume) provides a measure of the accretion rate density of the Universe. The nice thing about black holes, is that once matter has fallen into the black hole, it can't get back out.[1] As a consequence, integrating all these accretion rates over time gives the total amount of mass that accretes into a black hole in a given time interval. All we need to do, therefore, is measure the evolving AGN luminosity function and integrate it with respect to time to give total amount of mass (per unit volume) contained within today's black holes. Thankfully, since AGNs are bright, we are able to measure their luminosity function across large swathes of cosmic time and perform this calculation.

When astronomers integrate the evolving AGN luminosity function over cosmic time, they estimate that they get for the total amount of mass contained within black holes per cubic Mpc is about 5×10^5 $M_\odot$. Dividing this by the number density of massive galaxies in today's Universe (i.e., about 0.01 galaxies per Mpc^3 gives an average black hole mass of about 5×10^7 $M_\odot$ per massive galaxy. Again, this is far more massive than a typical stellar-mass black hole.

4.3 Weighing supermassive black holes

The above arguments make a strong case for the black holes at the hearts of AGNs to be supermassive (i.e., far more massive than normal, stellar mass black holes). They are, however, still just predictions. It would be nice to be able to actually measure the mass of these black holes directly. To do this we need to be able to measure the motion of "test particles" moving under the influence of the black hole's gravity.

4.3.1 Stellar orbits near the BH

One way to achieve this is by measuring the velocity of stars very close the black hole. However, the density of stars in the central regions of a galaxy is so high that the gravitational force of the central supermassive black hole only dominates (over the stars in the galaxy) within about 30 pc from the black hole. It took until the launch of the Hubble Space Telescope before these small scales could be anywhere near resolved in nearby galaxies.

Using the Hubble Space Telescope, astronomers in the mid-1990s measured the velocities of stars as a function of distance from the centres of two nearby galaxies: M84 and M87. What they found was that the stellar velocities showed a *sudden* turnover (i.e., from redshifted to blueshifted) within just a few parsecs of the central region. This demonstrates that whatever is governing the orbits of these stars must be incredibly compact (otherwise it wouldn't be such a sudden turnover). Indeed, based on these measurements, it was estimated that the central few parsecs of M87 contained a "dark" mass of 3.2×10^9 $M_\odot$ (i.e., it did not "shine" as much as you'd expect from a billion stars).

Later, in the early 2000s, aided with adaptive optics on ground-based near-infrared telescopes, astronomers measured the motions of stars around the central point of the Milky Way (known as Sagittarius A* and pinpointed via long baseline radio interferometry). In doing so, they discovered that the stars close to Sagittarius A* are orbiting a very massive, compact object (i.e., 4.3×10^6 $M_\odot$ that emits virtually no optical light. This object is so compact and massive that the only viable explanation is that it is a supermassive black hole at the centre of the Milky Way.

4.3.2 Reverberation mapping

The other main means of measuring the mass of a supermassive black hole involves using one of the main observable features of Type 1 AGNs as a test particle – the broad line region (BLR).

[1]At least, it's nice thing for this calculation, less so if you're the material falling in.

Under the assumption that the gas in the BLR moves under the influence of the black hole's gravity, we can use simple Newtonian dynamics to derive the black hole's mass:

$$M = \frac{v^2 r}{G} \tag{3}$$

where M is the mass of the black hole, G is the gravitational constant, v is the velocity of the clouds in the BLR and r is the radius of the BLR (i.e., equating $F = GMm/r^2$ and $F = mv^2/r$). We can easily measure v from the optical spectra of Type 1 AGNs, since the width of the emission lines gives a direct measurement of the circular velocity of the clouds via their doppler broadening.

By far the more difficult measurement to make, however, is the radius, r, of the BLR, since it is far too small to be resolved in even the most nearby AGNs. For this, astronomers exploit the variability of AGNs. When an AGN varies in brightness, this change propagates out from the central engine at the speed of light. After a certain amount of time (corresponding to the light travel time between the BLR and the central engine), we see the BLR respond to the change in luminosity of the nucleus (it is said to *reverberate* in luminosity in response to the change in luminosity of the central engine). By monitoring the luminosity of the central engine and BLR, and measuring how long it takes for the BLR to respond to a change in luminosity of the central engine, astronomers can determine the radius of the BLR. Typically it takes a BLR roughly a day or two to respond to a change in luminosity of the central engine, meaning that radius, r, of the BLR is roughly a couple of light-days. With a measurement of r, it is comparatively easy for astronomers to now calculate M.

Of course, since BLRs are only seen in Type 1 AGNs, reverberation mapping can only be used to measure the masses of black holes in Type 1 AGN (i.e., not non-AGN galaxies).

4.4 The Black Hole – Bulge relationship

Today, astronomers have measured the masses of hundreds of central supermassive black hole by one way or another. One remarkable outcome of this has been the realisation that the masses of the central supermassive black holes are remarkably well-correlated with the stellar mass of the bulge or spheroid in which they reside. This correlation spans over four orders of magnitude in both black hole mass and bulge mass.

The reason why this quite so remarkable is that, as we have seen, the gravitational influence of a supermassive black hole on the stars in its host bulge is extremely small. The black hole's gravity only dominates over that of the stars in the bulge for about 30pc, whereas a typical bulge will be many kiloparsecs across. Indeed, in terms of gravity, only about 1% of all the stars in a bulge "know" about the central supermassive black hole. A such, if it were based on purely gravity alone, we shouldn't expect there to be any relationship between the black hole and bulge, and yet we do see a tight correlation.

As we shall see later in the course, this tight correlation between the black hole mass and key properties of its host bulge has led many extragalactic astronomers to think there must be some interaction between black holes and their galaxies beyond gravity alone. This interaction is the "AGN feedback" that was referred-to in our discussions of the theory of galaxy evolution. We will cover this important aspect of galaxy evolution over the remaining few lectures.

5 Lecture 12 learning objectives

In this lecture we continued to look at the phenomena of AGNs, focussing mainly on the black hole and accretion disk that form the so-called "central engine". Here are the main learning objectives from this lecture:

- Have knowledge of the general properties of AGN: high nuclear luminosities; compact energy generation regions; long lifetimes; jets, peculiar spectra containing broad emission lines
- Understanding of why accretion of material by black holes is the most plausible energy generation mechanism for AGN
- Knowledge of the evidence for supermassive black holes in the nuclei of nearby galaxies (i.e., material on M84, M87, and the Milky Way) and AGNs.
- Awareness of the black hole – bulge relationship.