Active Galactic Nuclei & Quasars

1. Basics

Every massive galaxy contains supermassive black hole ($M > 10^5$ $M_\odot$) at its center (Kormendy & Ho 2013). In cases that gas is accreting onto the black hole, these can emit copious luminosity and are referred to as *active galactic nuclei*. Their bolometric luminosities can be from 10^{40} to 10^{47} erg s^{-1}, in the brighter cases outshining the rest of the galaxy.

The prevailing understanding of the structure of the emitting region is known as the *unification model* (Antonucci 1993; Netzer 2015). An accretion disk a few hundred Schwarschild radii in size emits a thermal *continuum* in the UV and optical, as well as in the X-rays. The accretion can power an outflowing *jet* visible in synchroton in the radio. Surrounding the accretion disk is a *broad line region* a few pc in size, consisting of dense clouds ($n > 10^4$ cm^{-3}); the Doppler broadening of these clouds orbiting the center of the galaxy is 1000s of km s^{-1}. Outside that region is a *narrow line region* a few hundred pc in size, also consisting of clouds but of lower density, and with a Doppler broadening of 100s of km s^{-1}. In between is a dusty region, possibly toroidal in shape, but in any case causing some the broad line region to be heavily extincted along at least some lines of sight. This picture was developed to explain the various observational classes of active galactic nuclei, as explained below.

There is an array of nomenclature associated with quasars. Below bolometric luminosities of around 10^{44} erg s^{-1} they are known as *Seyfert galaxies*. If broad line emission is visible, they are known as *Type 1*, and if it is not they are known as *Type 2*; there are also intermediate types occasionally defined. Depending on their radio flux, Seyferts and quasars are called *radio-loud* or *radio-quiet*; these terms are inconsistently used in the literature. Typically radio-loud refers to the criterion of Kellermann et al. (1989), who use $R = f_\nu(6\text{ cm})/f_\nu(4400\AA)$ and define radio-loud as $R > 10$. radio emission is detected, which very roughly often corresponds to $\nu L_\nu > 10^{41}$ erg s^{-1} or so. Depending on author, radio-quiet can either meaning not radio-loud, or undetected in the radio, or consistent with star forming radio emission.

1.1. Black hole accretion

Active galactic nuclei are powered by accretion. Matter accreting loses energy (and necessarily angular momentum) through some form of viscosity; the exact processes are not well-understood. This orbital energy loss heats the gas and the energy can be emitted radiatively. This process can proceed until the material reaches the innermost stable circular orbit, at $3r_S$, at which point the material does not need to lose energy to fall directly into the black hole. We quantify the efficiency of this process as a fraction ϵ of the rest mass energy (mc^2). The luminosity of the active galactic nucleus is then $\epsilon\dot{M}$, if $\dot{M}$ is the mass accretion rate. As shown in the exercises, the maximum efficiency of this process for a non-spinning black hole is about $\epsilon \sim 0.06$; it may be up to about 0.29 for a spinning black hole.

Regardless of the mass accretion rate, the luminosity is limited by the fact that if the luminosity is too high, outward radiation pressure on the surrounding material will prevent inward flow due to gravitational accelerations. The exercises derive this *Eddington limit*:

$$L_{\rm Edd} = \frac{4\pi G c m_p}{\sigma_T} \approx 1.26 \times 10^{38} \left(\frac{M_{\rm BH}}{M_\odot}\right) \text{ erg s}^{-1} \tag{1}$$

This limit implies that to reach $L \sim 10^{44}$ erg s^{-1} requires a black hole with a mass at least 10^6 $m_\odot$. Although this limit only strictly applies in spherical symmetry, estimates of black hole masses often imply luminosities of 0.01–0.1$L_{\rm Edd}$ for the most active AGN. Sometimes the Eddington limit is expressed as a mass accretion limit assuming some ϵ, but of course for a lower ϵ the mass accretion rate can exceed the limit.

If accreting gas has angular momentum, it will naturally form a disk of gas. The gas will experience viscosity. If the disk is Keplerian, this viscosity will naturally transport angular moment outward. The loss of angular momentum and the conversion of energy to heat allows the accretion. The disk may be optically thick and geometrically thin (Shakura & Sunyaev 1973). It can be shown in this case that the temperature profile will be:

$$T(r) = \left(\frac{3c^6}{64\pi G^2 \sigma_{SB}}\right)^{1/4} \left(\frac{r}{r_S}\right)^{-3/4} \dot{m}^{1/4} M^{-1/2} \tag{2}$$

The global resulting spectrum is the sum of the blackbody spectrum from all the radii. Generally, the spectrum will be hotter for lower mass black holes, or for more rapidly accreting black holes. AGN in this mode typically have $L > 0.01 L_{\rm Edd}$.

X-rays arise from the accretion disk. In AGN, the thermal continuum only provides substantial X-rays in the soft regime (< 2 keV). The higher energy X-rays are thought to arise from a coronal layer surrounding a thin accretion disk, similar to the solar corona. This hot corona can in principle be as hot as the virial temperature. Through inverse Compton scattering, it converts the disk continuum radiation into hard X-rays, extending in a power law spectrum $f_\nu \propto \nu^{-2}$ up to 100 keV.

However, a thin disk is not the only conceivable outcome for the accretion. An alternative possibility is that the disk (or some part of it) does not efficiently radiate the energy dissipated, in which case the disk can thicken. The resulting *advection dominated accretion flow* or *radiatively inefficient accretion flow* transports the thermal energy produced directly into the black hole through accretion, and thus is less efficient at turning gravitational energy into radiation (Narayan 2005). Theoretical models favor the creation of jets in this scenario, collimated by the inner edge of the thick disk. They also predict that these disks are hot, comparable to the virial temperature at each radius; X-rays arise both from Comptonization and from thermal brehmstrahlung.

1.2. Jet

In many systems, the accretion drives a jet of ionized gas outwards, in some cases hundreds of kpc in length; these jets are reviewed by Blandford et al. (2019). The jets often end in lobed structures. This jet is visible in the radio through synchrotron radiation with a power law spectrum. The radiating electrons are highly relativistic. The synchrotron radiation can be visible at higher frequencies, up through the optical. X-ray emission can be visible as well; the emission mechanism is disputed, but could be inverse Compton scattering of CMB photons or could be synchrotron self-Comptonization. The radio spectra have a variety of shapes which depend on the electron energy distribution and self-absorption.

The jets are typically moving at a high fraction of the speed of light, based on observed motions of features in the jets when resolved in the radio and optical. This causes the radiation to be beamed strongly along the jet axis; the $(1+z)^4$ effect of this blue or redshifting on the surface brightness causes the jet toward us to be detectable more often than the jet away from us.

The beaming can cause the inferred luminosity of the source to be extremely high if it is observed along the beam. This phenomenon is known as a *blazar*. The beamed synchrotron emission can overwhelm the ultraviolet-optical line and continuum emission, resulting in a pure power law continuum in the optical. This phenomenon is referred to as a *BL Lac* after the archetypal case. These sources are typically highly variable. If some line emission remains, the galaxy is known as an *optically violent variable (OVV)* star.

1.3. Broad line region

Many quasars and AGN exhibit broad emission lines with Doppler widths of order 10^4 km s^{-1}. These velocities imply a distance of a few hundred Schwarzschild radii from the central black hole, which translates into about 0.01 pc for a 10^8 $M_\odot$ black hole. Forbidden lines are not seen in these regions, which implies a high electron density, and from the presence of semiforbidden lines we infer $n_e \sim 10^{10}$ cm^{-3}. The ionization stages present imply temperatures of 2×10^4 K. With the density, temperature, and volume implied by these numbers, total emission from the gas then can be used to infer the filling factor, which is at the very most $f \sim 0.1$. From the total actual luminosity compared to the ionizing continuum flux, it can be inferred that the solid angle covered by the clouds is about 10%. These considerations lead to the picture of the broad line region as a large number of dense clouds surrounding the central black hole and its accretion disk.

1.4. Narrow line region

Essentially all quasars and AGN exhibit narrow optical emission lines, with widths of hundreds of km s^{-1} (typically broader than observed for non-AGN emission lines) indicating a region of a few hundred pc. The narrow line region can be resolved in many cases, and often has a biconical shape. The emitting lines include forbidden lines, with line ratios indicating densities of $n \sim 10^4$ cm^{-3} and temperatures of around 15,000 K. Like the broad line region, the filling factor can be shown to be low (~ 0.01) by comparing the density, temperature, and volume to the total emission.

Narrow forbidden lines are also excited in gas ionized by star-formation, hot evolved stars, and (more rarely) shocks. Emission line ratios can be used to distinguish the nature of the ionization source. The classic set of ratios are those published by Baldwin, Phillips, & Terlevich (BPT), the most commonly used of which is considering [NII]/Hα versus [OIII]/Hβ. The choices of emission line ratios are partly motivated by the desire to combine lines near the same wavelength, whose spectrophotometric and internal reddening correction errors will partly or mostly cancel. Seyfert galaxies have relatively high [NII]/Hα and very high [OIII]/Hβ. As shown in the exercises, the [OIII]/Hβ ratio is a good indicator of the ionization parameter.

A separate class of galaxies in the BPT diagram are low ionization galaxies, sometimes called LINERs, which have high [NII]/Hα but lower [OIII]/Hβ. Although some of these galaxies have active galactic nuclei, their emission is considerably more extended than that of the Seyferts and appears inconsistent with being ionized by a central source.

1.5. Dusty torus

Many galaxies exhibit narrow line AGN emission but no broad line or continuum emission in the optical and ultraviolet. However, the narrow line region must be ionized by some continuum. Furthermore, some galaxies have strong nuclear infrared emission. We believe that in these cases, the broad line and continuum regions are obscured by dust along our line of sight, which is in some anisotropic distribution such that along other lines of sight they would be visible. Usually this is described as a torus, but that specific geometry isn't necessary. To explain the observations, the dusty region should be larger that the broad line region, but smaller than the narrow line region. The most direct evidence for this hypothesis is the observation of broad lines in the polarization spectrum of narrow line AGN (see Antonucci 1993). The broad line region light is being scattered and polarized by gas in the narrow line region. These observations demonstrate that the dusty region does not obscure in all directions.

1.6. Variability

Quasars and active galactic nuclei are variable on time scales of a few weeks and above. Typically, the variability is anticorrelated with luminosity, with larger amplitude variability for less luminous objects. The variability in the continuum, which is likely due to accretion disk activity, typically occurs on shorter time scales for higher wavelengths, likely reflecting the dynamical time scale of the location of the emission. The line emission variability can be shown to lag the continuum, and the delay can be used to determine the radius of emission of the lines, and combined with their Doppler shifts, an estimate of the black hole mass; this technique is known as *reverberation mapping* (Peterson 1993). Occasionally even on a year-to-decade time scale active galactic nuclei and quasars have been known to turn off rapidly; the continuum and broad line emission disappears, but the narrow line emission (which extends for hundreds of lightyears) remains. This phenomenon is known as *changing look* (Green et al. 2022).

From the demographics and clustering of optically-bright quasars it is known that they are not in that state all of the time. From these considerations, *duty cycle* of quasars is estimated to be about 10^{-3} or so (e.g. Shankar et al. 2010). The total "on-time" for a quasar thus is limited to of order 10^7 years; it can be expected that this duration is not always contiguous in time. At lower Eddington ratios, this duty cycle must (by definition) be higher.

1.7. Luminosity function and evolution

The overall luminosity function can be converted into a black hole growth rate. The dependence of this growth rate on redshift is strong; the peak of black hole growth inferred is at $z \sim 2$–3 (**?**), with a steep decline after $z \sim 1$ and before $z \sim 3$. This growth rate evolution approximately follows the similar pattern of star formation rate density over cosmic time.

2. Important numbers

- $L_{\rm Edd} = 1.5 \times 10^{38} M_{\rm BH}/M_\odot$ erg s^{-1}

3. Key References

- *Revisiting the Unified Model of Active Galactic Nuclei (Netzer 2015)*
- Krolik *Active Galactic Nuclei: From the Central Black Hole to the Galactic Environment (Krolik 1999)*

4. Order-of-magnitude Exercises

1. Estimate the maximum efficiency of converting mass energy into emission for a non-rotating black hole of mass M.

   In order to fall deeper into a potential well, matter has to lose orbital energy and that energy is available for emission. In the case of a black hole, once it reaches the innermost stable circular orbit at $3r_s$, it can simply fall in without any further energy loss.

Using a Newtonian approximation, the orbital energy is $E = K + U = -U/2$. From infinity to $3r_s$ implies an energy loss per unit mass of $GM/6r_sc^2 = 1/12$, implying a maximum conversion efficiency of ~ 0.08. In a general relativistic calculation, the real energy available is slightly smaller than this (~ 0.06).

For a spinning black hole, the efficiency can be considerably higher.

2. Estimate efficiency of accretion
3. Estimate hottest gas in continuum
4. What is virial tempereature near disk
5. Doppler velocities to sizes
6. Critical density of CIII] and OIII
7. Estimate filling factor of BLR, NLR
8. Estimate duty cycle

5. Analytic Exercises

1. Eddington luminosity
2. Temperature profile of accretion disk
3. Relationship between energy distribution and synchrotron
4. Superluminal motion
5. Relativistic Beaming
6. Polarization

6. Numerics and Data Exercises

1. Quasar SEDs
2. Quasar variability
3. Densities from line ratios
4. Temperatures from line ratios
5. OIII/Hbeta and ionization parameter
6. resolved spectroscopy of AGN

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