11. Supermassive Black Holes

Angles in astronomy

If we can see that an object is extended (not just a point), we say it is *resolved*.

An object of diameter l at distance D subtends an angle

$$\theta = \frac{l}{D} \text{ radians} \tag{11.1}$$

This formula assumes $D \gg l$, which is almost always a good approximation in astronomy because objects are so far away.

With the naked eye, you can resolve objects about 10^{-3} radians across.

Because of blurring by the atmosphere, the sharpest images made by a good ground-based telescope are about 10^{-5} radians across.

This is the angle subtended by a quarter at a distance of about 2.5 km.

Hubble Space Telescope, above the earth's atmosphere, makes images with resolution of about 10^{-6} radians (limited by the size of its mirror).

An aside

Astronomers often quote angles in arc-seconds — for example, the bending of light by the sun is about 1.75 arc-seconds.

There are 3600 arc-seconds in 1 degree (like 3600 seconds in one hour), and 206,265 arc-seconds in a radian.

Resolved or unresolved?

The sun and the moon are both 1/2 degree across, about 0.01 radians.

The diameter of the sun is 400 times the diameter of the moon, but it is also 400 times further away.

Other stars are much further than the sun (60,000 times further for the closest one), so their angular sizes are much smaller, less than 10^{-6} radians.

They are *unresolved*, appearing as points of light.

Other galaxies are very large (l of 10,000 light years or more), so they are resolved, extended sources even when they are very far away (many millions of light years).

Giant clouds of gas in our own galaxy (the Milky Way) are resolved, extended sources in telescopes because they are big (a few light years across) and not *so* far away (a few thousand light years).

But black holes are very compact, so any image of a black hole and its immediate surroundings will be unresolved.

Basic Cosmology

In 1923, Edwin Hubble demonstrated that the "spiral nebulae" seen in telescopes are in fact distant galaxies, like the Milky Way.

Galaxies range widely in size, but a "typical" galaxy is roughly 100,000 light years across and contains 10-100 billion stars.

Over the next decade, Hubble's colleague Milton Humason showed that the spectral lines of most galaxies are shifted to the red, which suggests that they are moving away.

Hubble (1929): A galaxy's redshift is proportional to its distance (twice as far away $\Longrightarrow$ receding twice as fast). The universe is expanding.

This discovery, combined with theoretical calculations based on General Relativity, led to The Big Bang Theory: The universe has expanded from a very hot, very dense state, which existed at some finite time in the past (about 14 billion years ago).

Key points for our purposes:

- Stars are point sources of light, and their spectra show only small redshifts or blueshifts (up to a few hundred $\mathrm{km\,s^{-1}}$).
- Galaxies are extended sources of light, and their spectra are (nearly) aways redshifted, often by thousands or tens of thousands of $\mathrm{km\,s^{-1}}$.
- The higher the redshift the more distant the galaxy.

Angular resolution of a telescope

The angular resolution limit of a telescope with a mirror diameter D observing radiation of wavelength λ is

$$\theta_{\rm min} = \lambda/D \quad \text{radians}. \tag{11.2}$$

Only structure larger than $\theta_{\rm min}$ can be resolved.

Roughly speaking: the direction of waves of wavelength λ coming from directions less than $\theta_{\rm min}$ apart are not distinguishable.

This is a fundamental physical limit. Atmospheric blurring or imperfections in the mirrors (or radio antennas) may make images blurrier than this limit.

This limit is more severe for radio telescopes, because λ for radio waves is much larger than for visible light (by at least a factor of 10^4).

However, by carefully combining signals from telescopes separated by *distance* D, one can get some of the same resolution one would have from a single mirror or antenna of diameter D.

This challenging technique is called interferometry (because you have to get the waves to interfere with each other), and it is easier when the wavelength λ is longer.

The Discovery of Quasars

Early radio telescopes detected many sources over the sky.

Initially hard to identify with optical sources because of poor resolution of radio telescopes.

Resolution gradually improved by using interferometry with linked networks of radio telescopes.

Many sources appeared to coincide with galaxies.

Better resolution showed emission often coming from "lobes" on either side of galaxy, hundreds of thousands of light years from the stars.

A few sources appeared to coincide with stars.

Weird, "radio stars" not previously known.

Astronomers obtained visible light spectra for some of these sources.

Spectra showed lines at completely unknown wavelengths.

Maarten Schmidt (1963): Lines in the source 3C 273 are from hydrogen, but redshifted by 48,000 $\mathrm{km\,s^{-1}}$, 16% of the speed of light!

Lines in the source 3C 48 are from other kinds of atoms, redshifted by 37% of the speed of light.

Implication: These "points of light" are enormously distant and therefore enormously luminous, 100-1000 times more luminous than an entire galaxy of stars.

Named "quasars" for quasi-stellar radio sources, though we now also know many similar objects with little or no radio emission.

Quasar Energetics

Observed quasars have luminosities up to $5 \times 10^{13} L_\odot$ (or even more).

(The total luminosity of all stars in Milky Way is about $3 \times 10^{10} L_\odot$; the brightest quasars are more than 1000 times more luminous.)

Quasars vary substantially in brightness on timescales of days $\Longrightarrow$ *emission region must be at most a few light days across.*

Some quasars are associated with radio lobes and radio jets. The total energy in the lobes is around 10^{54} joules, about $10^7 M_\odot c^2$.

Accretion onto black holes is the only known energy source efficient enough to produce so much energy in such a small volume. The factor of $\frac{1}{12} \approx 0.1$ in the accretion formula means that an accretion disk is about ten times more efficient than fusion of hydrogen into helium (which converts only 0.01 of the hydrogen mass into energy).

The black holes must be massive or they could not emit so much energy without exceeding the Eddington luminosity limit.

The brightest quasars have luminosities equal to the Eddington limit for $M = 10^9 M_\odot$, or even a little higher.

Distinctive properties of quasars

Unlike typical stars, quasars emit their radiation over a wide range of photon energies: X-rays, UV light, visible light, infrared light; some are bright in radio waves and in γ-rays.

The properties of the emission are generally what we expect for accretion disks around supermassive black holes.

Also, the radio jets (and sometimes visible light or X-ray jets) that we see in some quasars could be produced by material ejected close to the speed of light, perpendicular to the accretion disk.

Jets can stay straight for millions of years because of the "gyroscope" provided by the spinning BH.

Especially significant: X-ray iron lines, which arise in hot gas fairly close to the event horizon, show large Doppler shifts and gravitational redshifts.

Quasar Demographics

Finding quasars:

- With visible light images alone, look for "stars" (points of light) with very weird colors.
- Or look for visible-light "stars" that have counterparts in X-rays or radio.
- To confirm that an object is a quasar, and measure its distance (from redshift), have to measure its spectrum.

There are now millions of quasars known.

The most distant known quasars have light redshifted by a factor of 11 $\Longrightarrow$ light emitted when universe was about 0.5 billion years old (compared to 14 billion years today).

Bright quasars were most common 10 billion years ago, much less common today.

The black holes themselves don't go away, so it must be that they are "fed" less often at later times.

Quasars and galaxies

Sharp imaging from *Hubble Space Telescope*, some ground-based telescopes $\Longrightarrow$ quasars live at the centers of the galaxies.

Sharp images needed because quasar can be much brighter than host galaxy itself.

Hosts often appear messed up, suggesting mergers of galaxies may trigger galactic scale gas flows that feed quasars.

Brighter quasars generally reside in bigger host galaxies.

Some galaxies (about 1-2%) have bright central nuclei, which appear to be scaled down versions of quasars, less luminous because black hole is less massive or because a massive black hole is being fed slowly.

We also find evidence for "dormant" black holes at the center of massive galaxies.

Their masses can be estimated from the motions of stars and gas near the center of the galaxy.

Doing this requires measuring near the center of galaxies, so that the gravity of the black hole dominates over the gravity of the stars.

The case for dormant black holes became much more convincing with *Hubble Space Telescope* because sharp imaging made it possible to measure much closer to galaxy centers.

Current evidence suggests that *all* galaxies with big central bulges of stars also have central supermassive black holes.

The BH mass and bulge mass appear to be tightly correlated, i.e., galaxies with more massive bulges have more massive central BHs.

Specifically, the mass of the black hole is typically about 1/1000 of the mass of stars in the bulge.

The Milky Way's black hole

As we have discussed the motions of stars near the center of the Milky Way imply that our galaxy has a central black hole with a mass of $4 \times 10^6 M_\odot$.

The total luminosity of this black hole (mostly in infrared and radio emission) is only about $100 L_\odot$, *very* far below Eddington limit.

It must be getting very thin dribble of gas (but not zero).

Summary of Empirical Evidence for Supermassive BHs

- High luminosity, rapid variability of quasars $\Longrightarrow$ enormous energy produced in a small volume. Accretion onto BH is only known mechanism to achieve this.
- Spectrum of radiation has properties expected for BH accretion.
- X-ray iron lines show large Doppler shifts and gravitational redshifts.
- Jets powering radio galaxies could come from BHs. No other ideas how to create such energetic jets or keep them so straight.
- Motions of stars at Galactic Center show large dark mass in small volume.
- Motions of stars and gas near centers of other galaxies show large dark mass in central regions.
- *New* (and discussed more later): Image of accretion flow and shadow cast by the event horizon from the $10^9 M_\odot$ BH in the galaxy Messier 87 and from the $4 \times 10^6 M_\odot$ BH in the center of the Milky Way.