Chapter 8

Active Galaxies

As briefly mentioned in section 7.2, an **active galaxy** is a galaxy in which much of the light is nonstellar, and much of the light comes from a small central nucleus. Active galaxies have many distinctive attributes.

- Active galaxies are **high in luminosity** ($L > 3 \times 10^{10} L_\odot$). Dwarf galaxies are never active galaxies.

- Active galaxies produce large amounts of **nonthermal emission**. That is, they have more radio and x-ray emission than you'd expect if all their light came from the hot photospheres of stars.

- Active galaxies have much of their light concentrated in a small central **nucleus**.

- Active galactic nuclei are **variable** on short time scales ($t \leq 1\,\mathrm{month}$).

- Active galactic nuclei have **jets** leading away from them, seen at both radio and visible wavelengths.

- Active galactic nuclei have strong **emission lines** in their spectra. These emission lines can be either extremely broad ($v \sim 10{,}000\,\mathrm{km\,s^{-1}}$) or relatively narrow ($v \sim 300\,\mathrm{km\,s^{-1}}$).

In order to be labeled as an active galaxy, a galaxy need not have every attribute listed above; it's more like a "choose any 4 out of 6" proposition. Moreover, even seemingly normal galaxies, like our own, have central nuclei where interesting and highly energetic phenomena are taking place. To understand active galactic nuclei, therefore, let's start close to home, by taking a journey to the center of our galaxy.

8.1 The Nucleus of Our Galaxy

The center of our galaxy is 8000 parsecs away from us, in the direction of Sagittarius. At a distance of 8000 parsecs, an angle of 1 arcsecond corresponds to a distance of $d = 8000\,\mathrm{AU} = 0.039\,\mathrm{pc}$. In the V band, there are $A_V = 28$ magnitudes of extinction between us and the Galactic center, which pretty well rules out observations at visible wavelengths. However, at infrared wavelengths of $\lambda \sim 2\,\mu\mathrm{m}$, there are only 2 magnitudes of extinction. Adaptive optics (mentioned in section 7.7 of *BA*) permits viewing the Galactic center at infrared wavelengths with a resolution of ~ 0.1 arcsec, as shown in Figure 8.1. This permits us to resolve structures as small as $d \sim 800\,\mathrm{AU}$ at

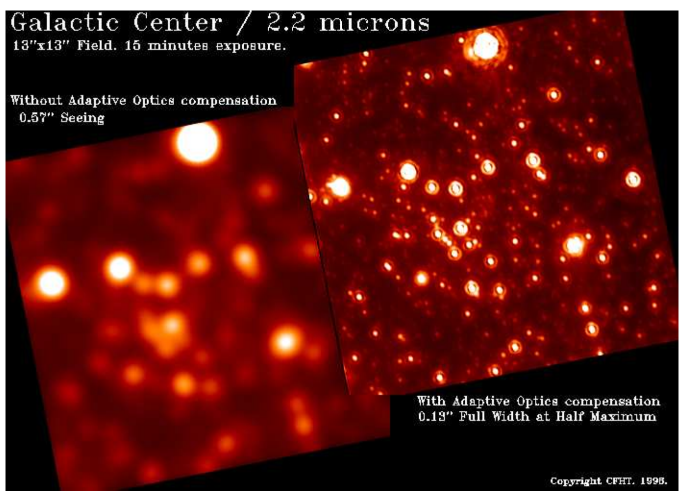

Figure 8.1: Stars in a region 0.5 parsecs on a side, near the Galactic center. Left image is without adaptive optics; right image is with adaptive optics.

the Galactic center. The stars in the infrared image of Figure 8.1 are mostly cool giants. If we assume that the ratio of giants to main sequence stars is the same at the Galactic center as in our neighborhood, we deduce that the number density of stars within a parsec of the center is $n_\star \sim 10^7\,\mathrm{pc}^{-3}$.

For comparison, the number density of stars in the solar neighborhood is $n \sim 0.1\,\mathrm{pc}^{-3}$. If the Sun were half a parsec from the Galactic center,

- The nearest star would be $\sim 1000\,\mathrm{AU}$ away.
- The night sky would contain $\sim 10^6$ stars brighter than Sirius.
- The total starlight would be ~ 200 times brighter than the full Moon.
- The probability of stars colliding would not be negligible.

The central regions of our galaxy would be a good place to study stars, but a bad place to study external galaxies, because of the high sky brightness.

At the center of our galaxy is a strong radio source called Sagittarius A. The total region of radio emission, shown in Figure 8.2, is about 50 parsecs across. The spectrum of the radio emission indicates that it is synchrotron

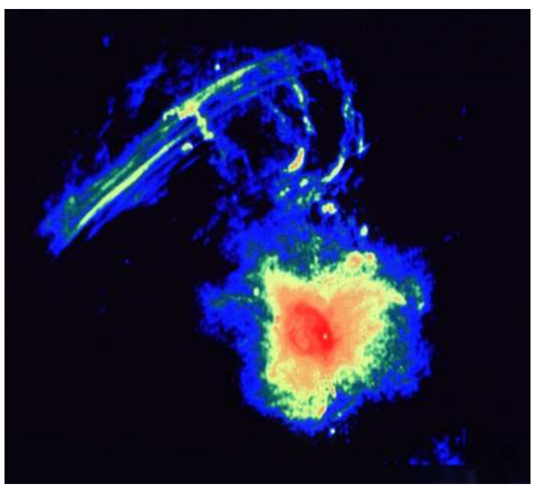

Figure 8.2: Sagittarius A, at $\lambda = 20\,\mathrm{cm}$. Box width is 25 arcmin, corresponding to $d \sim 60\,\mathrm{pc}$ at the Galactic center.

emission, produced by relativistic electrons accelerated by a magnetic field. The long prominences stretching away from Sagittarius A resemble solar prominences (*BA*, sec. 8.2) scaled up by a factor of one billion.

The early radio observations that detected Sagittarius A were of low angular resolution, and merely revealed the presence of an unresolved blob of radio emission. More recent observations have found detailed substructure in Sagittarius A. If we zoom in on the highest surface brightness region of Sagittarius A, we find an interesting radio source called Sagittarius A West, depicted in Figure 8.3. Sagittarius A West is a rotating mini-spiral of par-

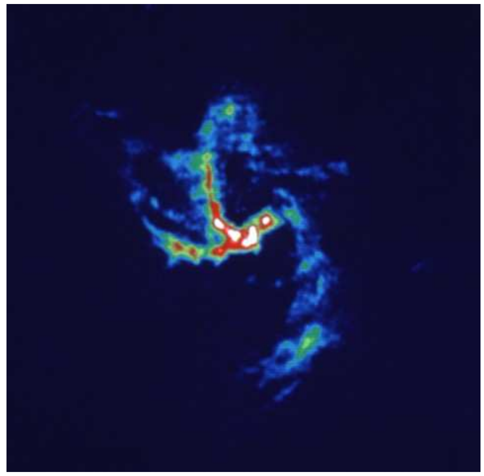

Figure 8.3: Sagittarius A West, at $\lambda = 6\,\mathrm{cm}$. Box width is 3 arcmin, corresponding to $d \sim 7\,\mathrm{pc}$ at the Galactic center.

tially ionized gas, about 5 parsecs across. Its radio spectrum looks much like that of an HII region, in which gas is excited by a central source of ultraviolet light. In the case of Sagittarius A West, the central source must be very luminous; but what is it?

If we zoom in on the center of Sagittarius A West, we find a highly compact radio source called **Sagittarius A***. (Don't look for a footnote; the asterisk is part of the name, which is pronounced "Sagittarius A Star".) The angular size of Sagittarius A* has been measured using radio interferometry. At a wavelength $\lambda = 7\,\mathrm{mm}$, the measured diameter of Sagittarius A* is $d'' \sim 0.8$ milliarcsec, corresponding to $d \sim 6\,\mathrm{AU}$ in physical units.[1] The high angular resolution provided by radio interferometry also enables a measurement of the proper motion of Sagittarius A*. Recent measurements reveal $\mu'' = (6.38 \pm 0.02) \times 10^{-3}\,\mathrm{arcsec\,yr^{-1}}$, directed almost entirely along the plane of the Milky Way. If Sagittarius A* were perfectly stationary at the Galactic center, we'd expect the Sun's motion about the Galactic center to produce a proper motion of $\mu \approx \omega_0 \approx 5.8 \times 10^{-3}\,\mathrm{arcsec\,yr^{-1}}$, as outlined in section 6.5.

[1] Thus, Sagittarius A* would fit easily inside the orbit of Jupiter.

Observations by the Chandra X-ray observatory reveal that Sagittarius A* is an X-ray source as well as a radio source. The X-ray emission from Sagittarius A* varies significantly on time scales of less than an hour, revealing that the majority of its X-ray emission must come from a region less than one light-hour ($\sim 7\,\mathrm{AU}$) across. Let's review what we know about Sagittarius A*: it is a fairly luminous, but highly compact, source of radio and X-ray emission, located at the Galactic center. (The bolometric luminosity of Sagittarius A* is not exactly known, due to the high extinction at many wavelengths, but is estimated to be $L \sim 1000 L_\odot$.) The leading hypothesis is that Sagittarius A* is a **supermassive black hole** that is accreting gas. A "supermassive" black hole is a black hole larger than you could make by simply letting a massive star collapse.

The black hole hypothesis is testable by looking at the motion of stars in the vicinity of Sagittarius A*. If there's a black hole present, with mass $M_{\rm bh}$ much greater than a stellar mass, then stars on elliptical orbits around the black hole will obey Kepler's Third Law:

$$M_\star + M_{\rm bh} = \frac{a^3}{P^2} \ , \tag{8.1}$$

where a is the semimajor axis of the star's orbit (in AU) and P is its orbital period (in years). Adaptive optics imaging at $\lambda \approx 2\,\mu\mathrm{m}$ has enabled astronomers to track a few bright stars near Sagittarius A* for more than a decade. One star, in particular, called "S0-2", has been observed to have a very small orbit (see Figure 8.4), with semimajor axis $a = 920\,\mathrm{AU}$ (assuming $R_0 = 8\,\mathrm{kpc}$) and orbital period $P = 14.5\,\mathrm{yr}$. The mass of the black hole is then given by the relation

$$M_\star + M_{\rm bh} = \frac{(920)^3}{(14.5)^2} M_\odot = 3.7 \times 10^6 M_\odot \ . \tag{8.2}$$

Since the star's mass is insignificant compared to that of the black hole, we can simply state $M_{\rm bh} = 3.7 \times 10^6 M_\odot$.

Within about 0.2 parsecs (or $40,000\,\mathrm{AU}$) of Sagittarius A*, all the stars are on Keplerian orbits, indicating that their dynamics are dictated by a single massive object at the center. Combining all the orbits of stars near Sagittarius A* yields a best estimate for the mass of

$$M_{\rm bh} = (3.7 \pm 0.2) \times 10^6 M_\odot \left(\frac{R_0}{8\,\mathrm{kpc}} \right)^3 \ , \tag{8.3}$$

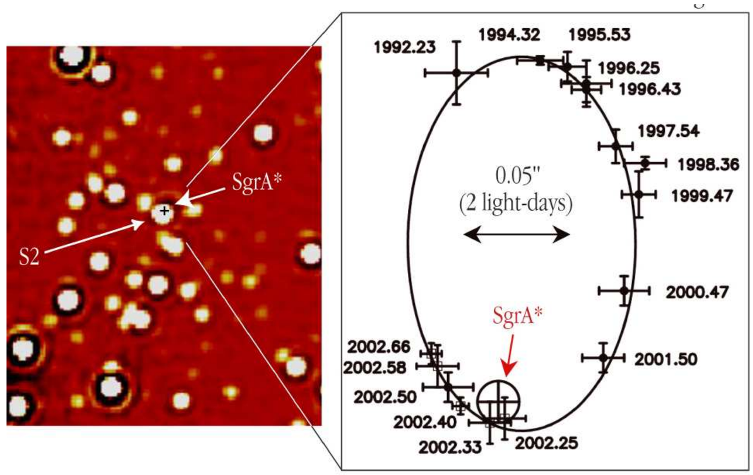

Figure 8.4: Orbit of the star S0-2 about the Galactic center. [Image credit: ESO]

indicating that the biggest uncertainty in the mass of the central supermassive black hole is provided by the uncertainty in R_0 (which in turn translates into an uncertainty in a for stars near the center). One of the stars near Sagittarius A*, named "S0-16", has an extremely eccentric ($e = 0.976$) elliptical orbit (Figure 8.5). At pericenter, S0-16 comes within 45 AU of Sagittarius A*. Since the star's orbit is neatly elliptical, with no detectable deviations from a Keplerian orbit, the massive object it is orbiting must be spherically symmetric, with a radius less than 45 AU. The only way to cram 3.7 million solar masses into a volume that small is to make it into a black hole.[2]

The Schwarzschild radius of a black hole with $M_{\rm bh} = 3.7 \times 10^6 M_\odot$ is $R_{\rm Sch} = 1.1 \times 10^7\,{\rm km} = 0.07\,{\rm AU}$, which subtends an angle of only 9 microarcseconds as seen from Earth. The radio and X-ray emission we see from Sagittarius A* comes from outside $R_{\rm Sch}$, more or less by definition. It is emitted by gas that is compressed and heated as it falls toward the black hole. In order to grow to a mass of $M_{\rm bh} = 3.7 \times 10^6 M_\odot$ during the Galaxy's lifetime of $t_{\rm mw} \sim 10\,{\rm Gyr}$, the black hole would have to accrete mass at an average rate

$$\frac{dM}{dt} = \frac{M_{\rm bh}}{t_{\rm mw}} \approx \frac{3.7 \times 10^6 M_\odot}{1.0 \times 10^{10}\,{\rm yr}} \approx \frac{1}{3000\,{\rm yr}} \ . \tag{8.4}$$

[2]If you tried to make a cluster of neutron stars, for instance, the neutron stars would collide and merge on a time scale short compared to the age of our galaxy.

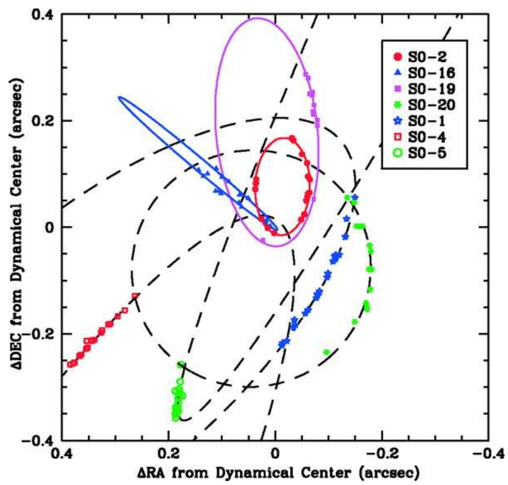

Figure 8.5: Orbits of all bright stars near the Galactic center. [Image credit: Ghez et al. 2005, ApJ, 620, 744]

By gobbling a solar mass of material every few millennia, the central black hole of our galaxy could have grown to its present mass.

In section 5.3 we learned that black holes less massive than $M_{\rm bh} \sim 2000 M_\odot$ would tidally rip you apart before you could reach the event horizon. Thus, if you wanted to dive into our galaxy's supermassive black hole, you wouldn't be tidally destroyed until after passing the event horizon. But what would happen to a star approaching the black hole? Stars are held together by gravitational forces. Thus, a star of mass $M_\star$ and radius $r_\star$ will be tidally ripped apart at a distance $r_{\rm rip}$ from the black hole's singularity. The distance $r_{\rm rip}$ is where the differential tidal force across the star,

$$\Delta F \approx \frac{G M_{\rm bh} M_\star}{r_{\rm rip}^3} r_\star \ , \tag{8.5}$$

is equal to the gravitational force holding the two halves of the star together,

$$F_{\rm grav} \approx \frac{G M_\star^2}{r_\star^2} \ . \tag{8.6}$$

By combining equations (8.5) and (8.6), we find that the star will be tidally disrupted at a distance

$$r_{\rm rip} \approx \left(\frac{M_{\rm bh}}{M_\star} \right)^{1/3} r_\star \ . \tag{8.7}$$

(This is the equivalent to the Roche limit for a moon orbiting a planet: see section 4-4 of *BA*.) A star similar to our Sun, for instance, would be ripped apart at a distance

$$r_{\rm rip} \approx 10^8\,{\rm km} \left(\frac{M_{\rm bh}}{3.7 \times 10^6 M_\odot} \right)^{1/3} \qquad (8.8)$$

from a supermassive black hole. When we compare this to the Schwarzschild radius of the black hole,

$$r_{\rm Sch} = \frac{2GM_{\rm bh}}{c^2} \approx 10^7\,{\rm km} \left(\frac{M_{\rm bh}}{3.7 \times 10^6 M_\odot} \right) \ , \qquad (8.9)$$

we find that Sun-like stars will be ripped apart before entering the event horizon so long as

$$M_{\rm bh} < \left(\frac{c^6 r_\odot^3}{8G^3 M_\odot} \right)^{1/2} \approx 2 \times 10^{38}\,{\rm kg} \approx 10^8 M_\odot \ . \qquad (8.10)$$

If a star is swallowed whole by a black hole, it doesn't produce a major outburst of radiation before it enters the event horizon. However, if the star is tidally shredded first, its gas forms a hot accretion disk around the star, and produces copious emission as it spirals in toward the event horizon.

8.2 Active Galactic Nuclei

Studying the spectra of gas and stars in the central regions of galaxies reveals that most, if not all, bright galaxies harbor a supermassive black hole at their center. For instance, M31 (the Andromeda Galaxy) has a black hole with $M_{\rm bh} \approx 5 \times 10^7 M_\odot$, over ten times the mass of our own supermassive black hole. Generally speaking, elliptical galaxies have a central black hole whose mass is proportional to the galaxy's luminosity L; (Figure 8.6). for spiral galaxies, the black hole mass is proportional to the luminosity of the galaxy's *bulge* alone (Figure 8.6). Thus, the black hole mass depends only on the 'bulge' component of a galaxy (we can think of an elliptical galaxy as being all bulge and no disk). Since $L \propto \sigma^4$ for elliptical galaxies and bulges of spiral galaxies, there is also a correlation between central black hole mass and the velocity dispersion σ of the 'bulge' component.[3]

[3] It's not really surprising that big galaxies have big black holes. Astronomers are surprised, however, at the tight correlation between $M_{\rm bh}$ and σ; when the velocity dispersion

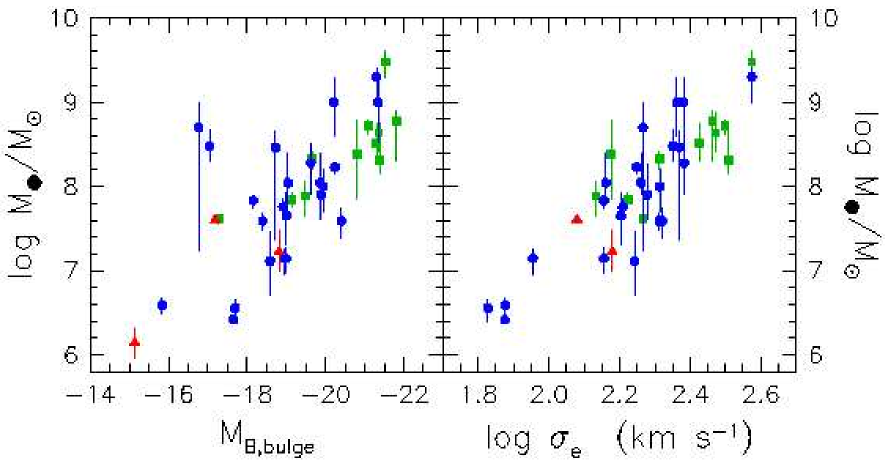

Figure 8.6: Left – Central black hole mass versus absolute magnitude of the 'bulge' component of the host galaxy. Right – Central black hole mass versus the velocity dispersion of the 'bulge' component.

Although bright galaxies contain supermassive black holes, not every bright galaxy is an active galaxy. A supermassive black hole is a necessary, but not sufficient, condition for having an active galactic nucleus. For an active galactic nucleus (AGN) to be present, the black hole must be accreting gas.

There exist different classes of AGNs, sorted by their observed properties. **Seyfert galaxies**, discovered by Carl Seyfert in the 1940s, are spiral galaxies with luminous, variable nuclei that have strong emission lines in their spectra. Seyfert galaxies have nuclei with $L \approx 10^{10} L_\odot \rightarrow 10^{12} L_\odot$. There are over 10,000 Seyfert galaxies known; it's estimated that about 1% of bright spiral galaxies are Seyferts. The spiral galaxy NGC 7742 (Figure 8.7) is a relatively nearby Seyfert galaxy. It is sometimes called the Fried Egg Galaxy; a name that seems appropriate when you look at its image.

Seyfert galaxies, although they all have strong emission lines, have interesting differences among their spectra. **Seyfert 1 galaxies** have extraordinarily broad Balmer emission lines, as shown in the top panel of Figure 8.8. If the broadening of the emission lines is due to Doppler shifts of hot gas

σ is measured, it is dominated by stars far enough out that the black hole has a negligible effect on their velocity. Why should a black hole's mass be so tightly correlated with the velocity of stars that are ignorant of its existence?

Figure 8.7: The Seyfert galaxy NGC 7742 ($d \sim 24\,\mathrm{Mpc}$). [Image credit: HST]

in motion, it must represent speeds of $v \approx 5000 \rightarrow 10{,}000\,\mathrm{km\,s^{-1}}$. By contrast, **Seyfert 2 galaxies**, as shown in the bottom panel of Figure 8.8, have much narrower Balmer emission lines. The width of the absorption lines in a Seyfert 2 galaxy correspond to only $v = 200 \rightarrow 400\,\mathrm{km\,s^{-1}}$. If the emission lines in a Seyfert galaxy come from gas orbiting a supermassive black hole, then the light from Seyfert 1 galaxies comes from much closer to the event horizon, where the orbital speeds are higher.

Another class of AGNs consists of **BL Lac** objects. Unlike Seyfert galaxies, which are named after their discoverer, BL Lac objects are named after their prototype, BL Lacertae. The name "BL Lacertae" is the type of name (two letters plus a constellation name) that is given to a variable star. In fact, BL Lacertae was originally thought to be a variable star within our own galaxy! However, longer exposures (Figure 8.9) reveal that BL Lacertae is a distant elliptical galaxy; its redshift of $z \approx 0.07$ puts it at a distance $d \approx (c/H_0)z \approx 300\,\mathrm{Mpc}$. The reason why BL Lacertae was originally mistaken for a star was that its unresolved nucleus is brighter than the diffuse fuzz of starlight surrounding it. The nuclei of BL Lac objects are rapidly variable, and have a nonthermal spectrum, but do not show any emission lines. This makes it difficult to determine the distance to a BL Lac object, unless you can manage to detect the absorption lines in the fuzz of starlight. This is very difficult for many BL Lac objects, since their nuclei are so ex-

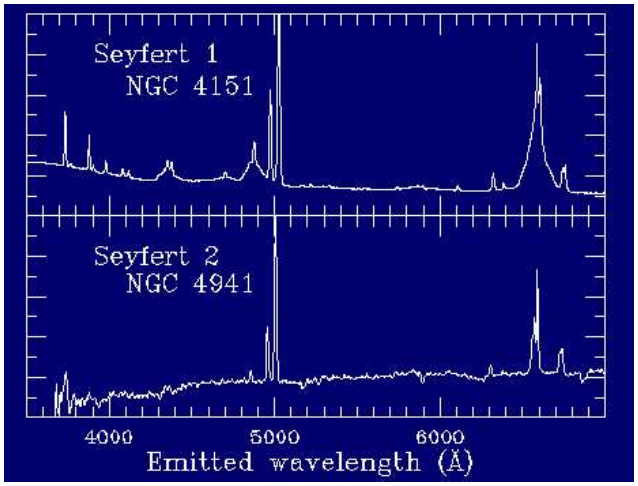

Figure 8.8: Top – spectrum of a Seyfert 1 (broad lines). Bottom – spectrum of a Seyfert 2 (narrower lines).

traordinarily luminous compared to their stars. (It also makes it difficult to determine their morphology; it's conjectured that all BL Lac objects are ellipticals, but no one seems to be totally sure.) The flux from a BL Lac object can change significantly from one night to the next; this indicates that the bulk of the luminosity comes from a region less than one light-day ($\sim 200\,\mathrm{AU}$) across.

Seyfert galaxies were first noticed because someone looked at images of spiral galaxies and said, "Wow! Those nuclei are really bright!" BL Lac objects were first noticed because someone looked at the radio emission from BL Lacertae and said, "Wow! That's way too much radio emission for BL Lacertae to be a star!"

Another class of active galaxies is the **radio galaxies**. Radio galaxies are defined, simply enough, as galaxies that have strong radio emission. Sometimes it is stated that radio galaxies must have $L_{\mathrm{radio}} > 10^{33}\,\mathrm{W} \sim 3 \times 10^6 L_\odot$ at radio wavelengths, but that's a fairly arbitrary cutoff, chosen because a bright but inactive spiral galaxy – like our own galaxy – has $L_{\mathrm{radio}} \sim 10^{33}\,\mathrm{W}$ from its interstellar gas. The strongest radio galaxies have $L_{\mathrm{radio}} \sim 10^{38}\,\mathrm{W} \sim 3 \times 10^{11} L_\odot$. Strong radio sources are most frequently associated with elliptical galaxies, but sometimes (in the case of Centaurus A, for instance), radio galaxies are classified as "peculiar".

In a radio galaxy, the radio emission is not necessarily confined to a central

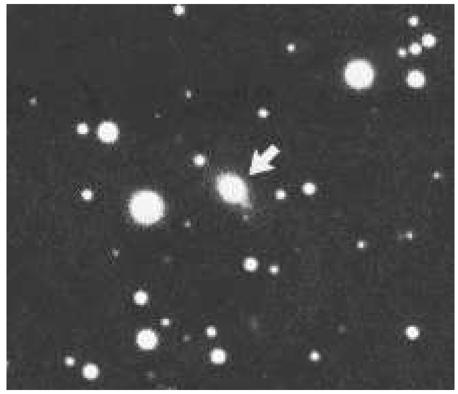

Figure 8.9: The active galaxy BL Lacertae (arrowed).

nucleus. **Extended** radio galaxies have long jets which can be much bigger than the image of the galaxy at visible wavelengths. For instance, Centaurus A is an extended radio galaxy; Figure 8.10 shows the long radio jets of Centaurus A superimposed on its optical image. The jets of an extended

Figure 8.10: False color radio map of the extended radio galaxy Centaurus A, combined with an visible-light image.

radio galaxy can be over a megaparsec long.

Compact radio galaxies have smaller jets, frequently accompanied by an unresolved radio source at the galaxy's nucleus. To find a compact radio galaxy, we need go no further than the nearby Virgo Cluster of galaxies. The galaxy M87, a bright elliptical galaxy near the cluster's center, goes under the alias “Virgo A”, indicating that it’s the highest-flux radio source in the constellation Virgo. In the central regions of M87, there’s a 2 kpc long jet

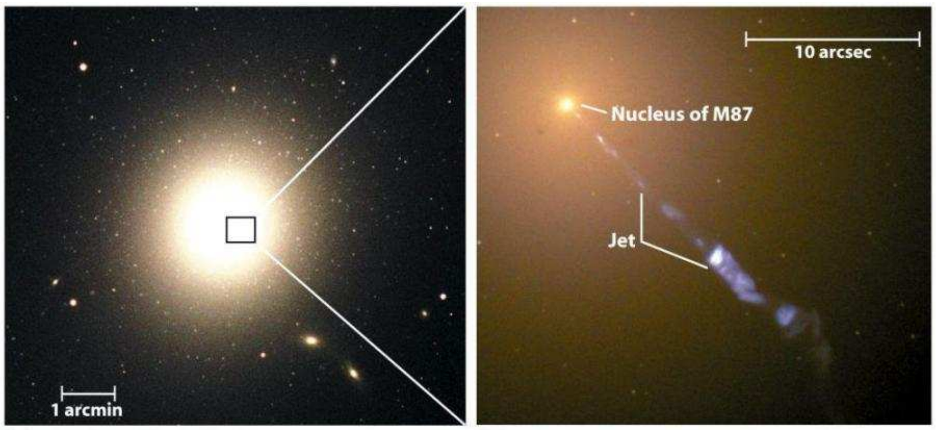

Figure 8.11: The elliptical galaxy M87, with close-up of its nucleus and jet.

seen at radio, visible, and X-ray wavelengths (Figure 8.11). Hubble Space Telescope imaging of the central regions reveals a gas disk perpendicular to the jet. The disk (Figure 8.12) looks like the mini-spiral of hot gas in the center of our own galaxy, only an order of magnitude bigger. The radius of the central disk in M87 is $r = 16\,\mathrm{pc} = 4.9 \times 10^{17}\,\mathrm{m}$; we are seeing it at an inclination $i = 42°$. The observed spectrum of the disk reveals that it is rotating with

$$v_c \sin i = 460\,\mathrm{km\,s^{-1}} , \tag{8.11}$$

or $v_c = 690\,\mathrm{km\,s^{-1}}$. We can then calculate that the mass within 16 pc of the center is

$$M = \frac{v_c^2 r}{G} \approx 4 \times 10^{39}\,\mathrm{kg} \approx 2 \times 10^9 M_\odot . \tag{8.12}$$

This mass is primarily due to the supermassive black hole at the center of M87.[4]

Seyfert galaxies, BL Lac objects, and radio galaxies seem to be something of a mixed bag, with different morphologies and spectra. However, astronomers have built up a **Unified Model** of AGNs. At the heart of every AGN, this model states, there is a supermassive black hole. Spectroscopic

[4]Perhaps we should call it a “hypermassive” black hole, since it is more than 500 times the mass of the relatively dainty black hole at the center of our galaxy.

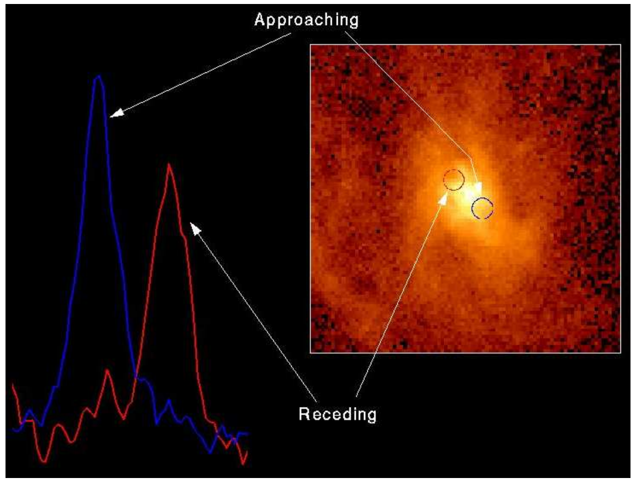

Figure 8.12: Gas disk at the center of M87, with Doppler shift information. [Image credit: HST]

evidence for this black hole comes in the form of high-speed stars and gas near the galaxy's nucleus. Gas forms an accretion disk around the black hole. The gas, as it spirals in toward the event horizon, is heated up as gravitational potential energy is converted to thermal energy. The accretion disk will be very hot in its inner regions; the outer regions will be cool enough to contain dust (which vaporizes at $T \sim 2000\,\mathrm{K}$) as well as gas. Generally, the outer regions of the disk will be puffed up into a torus, as illustrated in Figure 8.13. Some of the hot gas in the disk slips through the event horizon, boosting the mass of the black hole. Some ionized gas is ripped from the accretion disk by electromagnetic fields, and spirals along magnetic field lines away from the disk, forming a jet. The accelerated electrons in the ionized gas emit synchrotron emission, accounting for the radio emission from the jet.

The type of AGN that you see from Earth depends on the orientation of the toroidal disk relative to the line of sight. If you look directly along the jet (vector 4 in Figure 8.13), you see primarily synchrotron emission from the jet. In In this case, you see the featureless continuum spectrum characteristic of BL Lac objects. If you look at an angle close to the jet (vector 3), you get a good look at the Broad Line Region (BLR); that is, the region close to the event horizon where gas is moving very rapidly. In this case, you see broad emission lines from the rapidly moving gas, and the AGN is classified

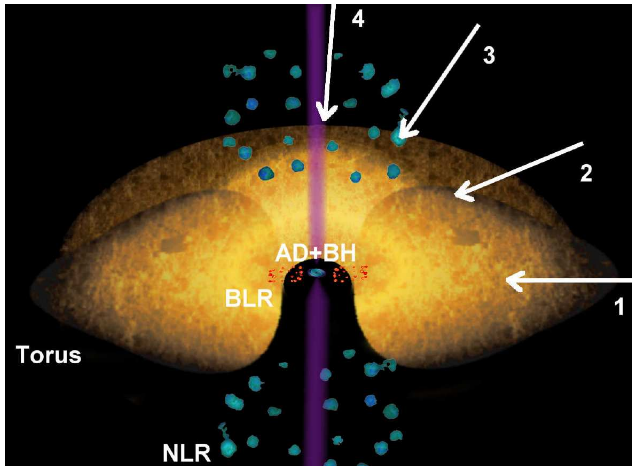

Figure 8.13: Unified Model of Active Galactic Nuclei.

as a Seyfert 1 galaxy. If you look at an angle close to the disk (vector 1), the Broad Line Region is hidden from you by dust, and you can only see the Narrow Line Region (NLR), farther from the central black hole. In this case, you see narrow emission lines, and the AGN is classified as a Seyfert 2 galaxy. At some angles (vector 2), you are playing peek-a-boo with the edge of the disk, and the width of emission lines can vary as the disk swells and shrinks.

As matter falls toward a black hole, a large amount of energy can conceivably be extracted from it. Suppose a mass m falls from a large distance $r \gg r_{\rm Sch}$ toward the Schwarzschild radius $r_{\rm Sch} = 2GM_{\rm bh}/c^2$ of a black hole. Its loss of gravitational energy will be

$$\Delta E = -\frac{GM_{\rm bh}m}{r} + \frac{GM_{\rm bh}m}{r_{\rm Sch}} \approx \frac{GM_{\rm bh}m}{r_{\rm Sch}} \approx \frac{1}{2}mc^2 \ . \qquad (8.13)$$

If the mass isn't halted before reaching the Schwarzschild radius, it will pass the event horizon with a speed $v \sim c/\sqrt{2}$, and its kinetic energy will go to swell the mass of the black hole. If the mass is decelerated by slamming into an accretion disk, its kinetic energy will be converted into thermal energy, and then into photon energy. The conversion of gravitational potential energy (equation 8.13) into photon energy is not perfectly efficient. (Some of the energy, for instance, goes into the kinetic energy of the outflowing jets.) It is customary to write the energy carried away by photons as

$$\Delta E_{\rm phot} = \eta mc^2 \ , \qquad (8.14)$$

where η is a dimensionless number, sometimes called the "efficiency" of the black hole. From equation (8.13), we expect $\eta \leq 1/2$. In practice, it is thought that a typical active galactic nucleus has

$$\eta \approx 0.1 \ , \tag{8.15}$$

which means that a single gram of matter falling toward the central black hole yields 9 trillion joules of radiation energy.

As gas feeds into the black hole at a rate $\dot{M}$, the luminosity of the AGN is

$$L = \eta \dot{M} c^2 \ . \tag{8.16}$$

If we know an AGN's luminosity, we can then deduce its infall rate $\dot{M}$:

$$\dot{M} = \frac{L}{\eta c^2} = 0.018 M_\odot \, \mathrm{yr}^{-1} \left(\frac{L}{10^{37}\,\mathrm{W}} \right) \left(\frac{\eta}{0.1} \right)^{-1} \ . \tag{8.17}$$

In general, we don't expect $\dot{M}$ to be constant with time, accounting for the variability detected in the luminosity of AGNs. The low luminosity of the Milky Way's central black hole, $L \sim 1000 L_\odot \sim 4 \times 10^{29}\,\mathrm{W}$, implies either a low infall rate at the present moment ($\dot{M} \sim 10^{-9} M_\odot \,\mathrm{yr}^{-1}$), or a low efficiency, or both.

8.3 Quasars

You might think that by shoveling in matter at higher and higher rates, you can make an active galactic nucleus have arbitrarily high luminosity. In fact, there exists a maximum permissible luminosity for a given black hole mass $M_{\rm bh}$; crank up the luminosity too high, and the gas surrounding the black hole will be blown away by radiation pressure. Consider an accreting black hole of mass $M_{\rm bh}$ and luminosity $L = \eta \dot{M} c^2$. Let's assume that the black hole is surrounded by ionized hydrogen.[5]

At a distance r from the active nucleus, the photons have an energy flux

$$f = \frac{L}{4\pi r^2} \ . \tag{8.18}$$

[5] It's natural that the gas should be ionized, since it's heated as it falls toward the black hole. The assumption that it's pure hydrogen is simply to make the calculation easier.

In addition to an energy E, each photon has a momentum $p = E/c$. Thus, the outward flow of photons creates a *momentum flux*

$$f_p = \frac{f}{c} = \frac{1}{c}\frac{L}{4\pi r^2} \ . \tag{8.19}$$

Because the photons carry momentum, they can exert a force on the free electrons and protons in the ionized hydrogen. The force exerted on each particle is the rate at which momentum is transfered to it. The rate of momentum transfer depends in turn on the particle's cross-section for interaction with photons. Electrons have a much larger cross-section for photon interactions than protons do.[6] For electrons, the relevant cross-section is the Thomson cross-section,

$$\sigma_T = 6.65 \times 10^{-29}\,\mathrm{m}^2 \ . \tag{8.20}$$

The electron feels an outward force due to radiation pressure. The amplitude of the force is equal to the momentum flux times the electron's cross-section:

$$F_{\rm rad} = \sigma_T f_p = \frac{\sigma_T L}{c 4\pi r^2} \ . \tag{8.21}$$

As the electron is accelerated, it drags the nearest proton along with it, which maintains charge neutrality. Thus, every electron is burdened with a massive proton which it drags along like a ball and chain.

The inward force on the electron-proton pair is provided by gravity:

$$F_{\rm grav} = -\frac{GM_{\rm bh}(m_p + m_e)}{r^2} \approx -\frac{GM_{\rm bh} m_p}{r^2} \ , \tag{8.22}$$

since the electron mass m_e is insignificant compared to the proton mass m_p. The maximum possible luminosity for the accreting black hole is called the **Eddington luminosity**, after the astronomer Arthur Eddington. The Eddington luminosity L_E is the luminosity at which the outward radiation force exactly equals the inward gravitational force:

$$\frac{\sigma_T L_E}{c 4\pi r^2} = \frac{GM_{\rm bh} m_p}{r^2} \ . \tag{8.23}$$

[6] The cross-section goes as $1/m^2$, where m is the particle mass. Since electrons are less massive than protons by a factor $\sim 1/2000$, they have larger cross-sections by a factor ~ 4 million.

Note that the factors of r^2 cancel: the ratio of radiation force to gravitational force is independent of distance from the black hole. The Eddington luminosity for a black hole of mass $M_{\rm bh}$ is

$$\begin{aligned} L_E = \frac{4\pi G m_p c}{\sigma_T} M_{\rm bh} &= 1.3 \times 10^{40}\,{\rm W} \left(\frac{M_{\rm bh}}{10^9 M_\odot}\right) \\ &= 3.3 \times 10^{13} L_\odot \left(\frac{M_{\rm bh}}{10^9 M_\odot}\right) . \end{aligned} \tag{8.24}$$

If the luminosity is greater than L_E, then the ionized gas will be accelerated outward, and accretion will cease.[7] The existence of a maximum luminosity L_E leads to a maximum accretion rate for black holes:

$$\dot{M}_E = \frac{L_E}{\eta c^2} = 20 M_\odot\,{\rm yr}^{-1} \left(\frac{M_{\rm bh}}{10^9 M_\odot}\right) \left(\frac{\eta}{0.1}\right)^{-1} . \tag{8.25}$$

If you try to feed a black hole more rapidly than this, it spits the gas back out.

The question of how luminous an AGN can be is important when we discuss the most luminous AGNs of all: the **quasars**. The term "quasar" is short for **quas**istell**ar** object.[8] A quasar is an active galactic nucleus which has a very high luminosity: $L > 10^{38}\,$W, or so. The most luminous known quasars have $L \sim 10^{41}\,{\rm W} \sim 3 \times 10^{14} L_\odot \sim 10^4 L_{\rm MW}$. Because quasars are so luminous compared to the stellar "fuzz" of the galaxies in which they are embedded, they usually appear like unresolved points of light, just like stars – hence the term "quasistellar". For instance, Figure 8.14 shows the quasar 3C273, the first quasar to be discovered.[9] Note how the quasar more strongly resembles the stars in the field of view than the two fuzzy, extended galaxies at the left of the figure.

The discovery of quasars had its origin in the 1960s, when some strong radio sources, such as 3C273, were identified with unresolved point sources of

[7] Brief aside about stars: Scaled to the Sun's mass, $L_E = 33{,}000 L_\odot (M/1M_\odot)$. Since the luminosity of high-mass stars is $L \approx 1L_\odot(M/1M_\odot)^4$, this implies that stars with $M > 32M_\odot$ will have $L > L_E$. Thus, the Eddington luminosity imposes an upper mass limit on stars. A hypermassive star would blow itself apart, with the outer layers being lost in a radiation-driven wind.

[8] An alternate term for "quasar" is "QSO", which is also short for **Q**uasi**S**tellar **O**bject.

[9] Many quasars have names that start with "3C". This is their catalog number in the 3rd Cambridge Catalog of radio sources.

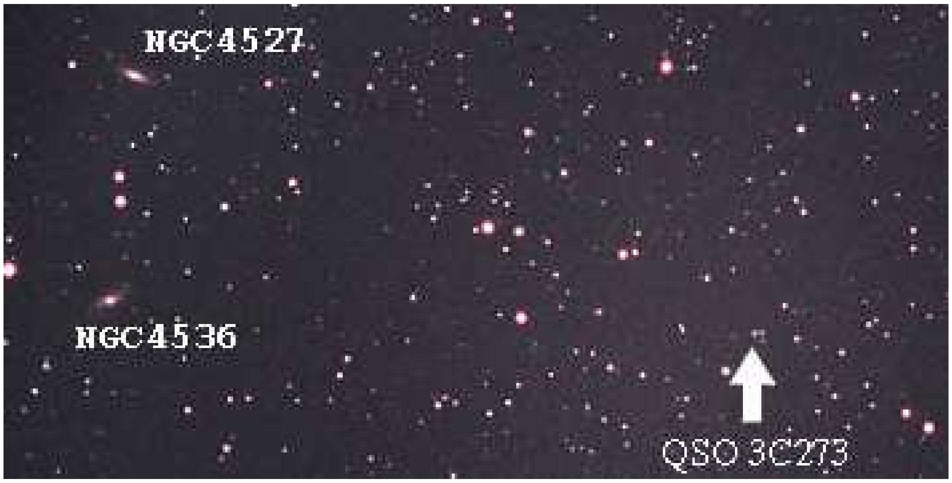

Figure 8.14: Quasar 3C273, and two galaxies, NGC 4527 and NGC 4536.

light. This was unusual; stars are not generally strong radio sources. When the spectra of these quasistellar radio sources were taken, thing became more unusual still. The spectra contained emission lines which didn't correspond to any known element. The breakthrough to understanding came in 1963, when Maarten Schmidt had a "eureka" moment while looking at the spectrum of 3C273 (Figure 8.15). He realized that the emission lines in the spectrum were Balmer lines with a redshift $z = 0.158$. No one had been expecting such a high redshift. It corresponds to a radial velocity $v_r \approx cz \approx 47{,}000\,\mathrm{km\,s^{-1}}$ and a distance $d \approx (c/H_0)z \approx 680\,\mathrm{Mpc}$. The redshifts of currently known quasars range from $z = 0.06$ to $z = 6.4$.

How do we know that quasars are active galactic nuclei, rather than something even more exotic? Let's look at the properties of quasars.

- Quasars are very **high in luminosity**. The most luminous quasars have $L \sim 3 \times 10^{14} L_\odot$. This implies an accretion rate of $\sim 200 M_\odot\,\mathrm{yr^{-1}}$, assuming $\eta \sim 0.1$, and a black hole mass of $M_{\rm bh} > 8 \times 10^9 M_\odot$ if the quasar is to remain below its Eddington luminosity.

- Quasars produce **nonthermal emission**. Many quasars are strong radio sources; most quasars are strong X-ray sources.

- Quasars have almost all their light concentrated in their **nucleus**.

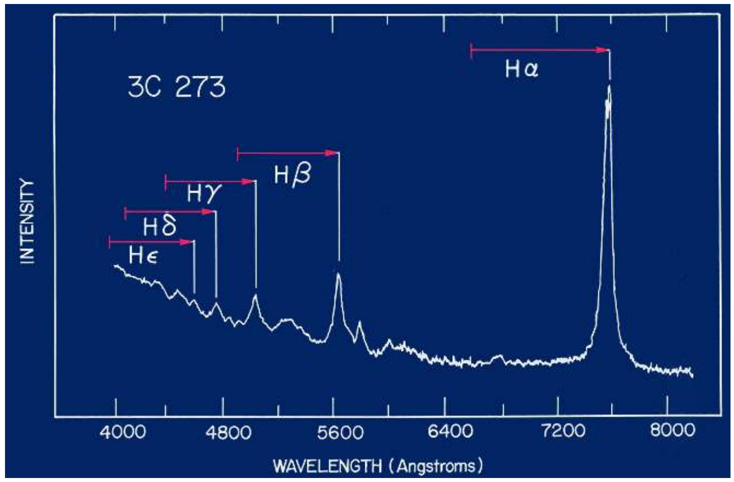

Figure 8.15: Spectrum of the quasar 3C273, showing redshifted Balmer lines.

- Quasars are **variable** on short time scales; sometimes as short as $t \sim 1\,\text{day}$.
- Quasars sometimes have **jets**. A high-resolution, long-exposure image of 3C273 (Figure 8.16) reveals a long jet, for instance.
- Quasars have strong **emission lines** in their spectrum.

In other words, quasars have all the observed properties of active galactic nuclei, as listed at the beginning of this chapter. If they look like ducks, fly like ducks, and quack like ducks, let's call them ducks (even if they happen to be darned big ducks!) Since the emission lines of quasars are extremely broad, their spectra are similar to those of Seyfert 1 galaxies. About 10% of quasars have strong radio emission, and are called "radio loud" quasars. The remaining quasars are "radio quiet".

Astronomers are fond of the saying "A telescope is a time machine". As we look farther out in space, we are looking farther back in time. When we look at 3C273, two billion light years away, we are seeing it as it was 2 billion years ago. When we look at the quasar with the highest known redshift, $z = 6.4$, the relativistically correct equations tell us that we are looking at a quasar that is currently 27 billion light years away, and we are seeing it as it was 13 billion years ago.[10] We know from the measured masses of black

[10]The $z = 6.4$ quasar is currently more than 13 billion light years away because the

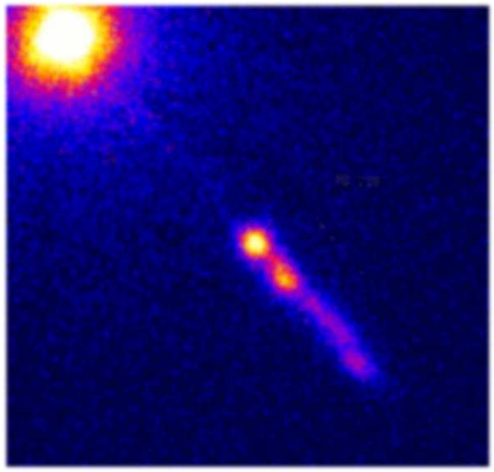

Figure 8.16: The jet of the quasar 3C273, seen at X-ray wavelengths. [Image credit: Chandra]

holes today that quasars must have relatively short lives. The most luminous quasars, with $L \approx 3 \times 10^{14} L_\odot$, must have accretion rates $\dot{M} \approx 200 M_\odot \,\mathrm{yr}^{-1}$ to maintain that luminosity. The biggest supermassive black holes today have $M_{\rm bh} \sim 4 \times 10^9 M_\odot$. To grow to that mass at the maximum accretion rate would take a time

$$t \approx \frac{M_{\rm bh}}{\dot{M}} \approx \frac{4 \times 10^9 M_\odot}{200 M_\odot \,\mathrm{yr}^{-1}} \approx 20\,\mathrm{Myr}\ . \tag{8.26}$$

If the most luminous quasars maintained their luminosity for the age of the universe ($\sim 14\,\mathrm{Gyr}$), they would grow to $\sim 3 \times 10^{12} M_\odot$ by the present day.

When we compute the number density of quasars as a function of redshift, we find that there were many more quasars in the past than there are now. At the present moment, only one in a million bright galaxies is a quasar. When the universe was about 20% of its present age (That is, when it was $\sim 2.7\,\mathrm{Gyr}$ old), about one in a thousand bright galaxies was a quasar. The black holes that accreted gas and drove the luminosity of the quasars haven't gone away. Black holes only grow more massive with time.[11] This means that

distance between us and it has been constantly stretching during the past 13 billion years. At the time the quasar emitted the light that we see today, it was only 3.7 billion light years away.

[11]Unless they are very tiny, in which case Hawking radiation makes them evaporate.

the black holes that powered quasars are still around today, bigger and fatter than ever. They are just less luminous because they are being fed gas at a lower rate. Old quasars never die – they just go into hibernation when there's nothing to eat.

One reason why supermassive black holes accreted gas more rapidly in the past is hinted at when you look at the high-redshift galaxies that host quasars (Figure 8.17). Although some quasar hosts are fairly normal looking spiral

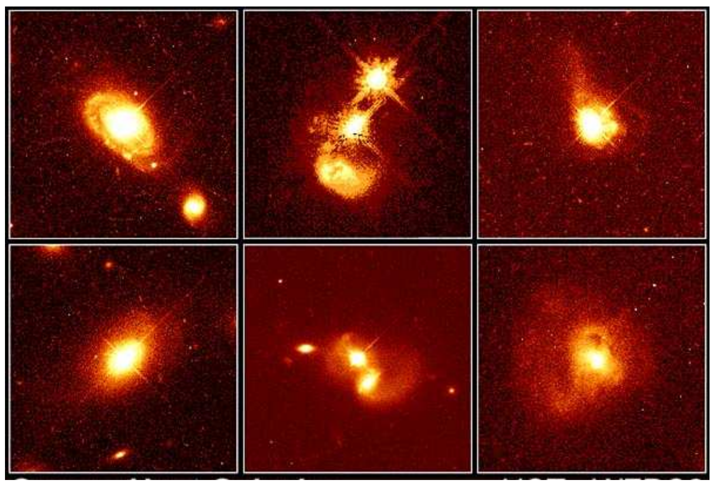

Figure 8.17: Host galaxies of six quasars ($d \sim 400 \rightarrow 900\,\mathrm{Mpc}$). [Image credit: HST]

and elliptical galaxies (left panels in Figure 8.17), most are peculiar-looking galaxies in the process of merging. Galaxy mergers were more common in the past than they are now – in an expanding universe, galaxies were closer together in the past. When galaxies merge, their gas clouds collide, lose angular momentum, and fall to the center of the merged galaxy, where the black hole(s) are ready to accrete them.[12]

Quasars are interesting not merely for their own sake, but because they act as probes of the **intergalactic medium**. Light from quasars hundreds of megaparsecs away must pass through hundreds of megaparsecs of intergalactic gas before it reaches us. Just as stellar spectra can show absorption

[12]When two galaxies, each with a central supermassive black hole, merge to form a new, larger galaxy, it is not known with certainty how long it takes for their two black holes to become one. They may just form a stable black hole binary at the center of the new galaxy.

lines from interstellar gas clouds (section 4.2), quasar spectra can show absorption lines from intergalactic gas. Because the gas clouds between us and the quasar are at a smaller distance d than the quasar (Figure 8.18), they have a smaller redshift z. Thus, the absorption lines are at shorter wave-

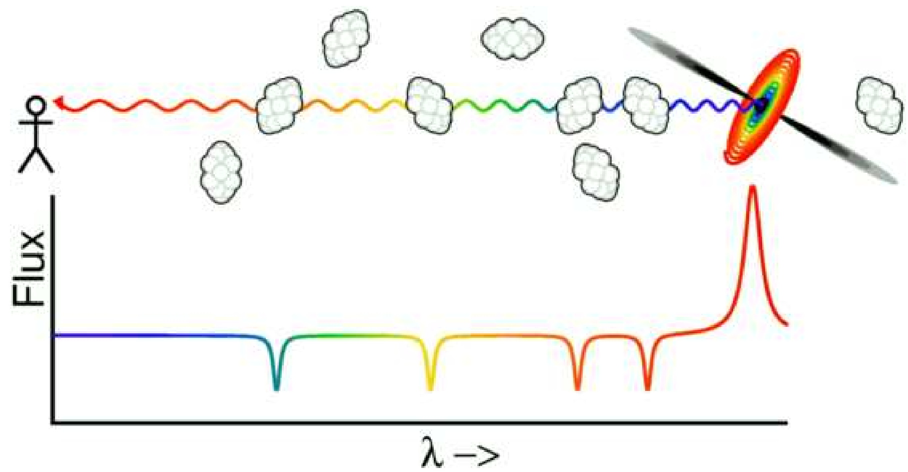

Figure 8.18: Absorption by gas clouds along the line of sight to a quasar.

lengths than the corresponding emission line from the quasar itself. As an example, consider the Lyman alpha line of neutral hydrogen, which has a rest wavelength of $\lambda_0 = 1216\,\text{Å}$. The quasar QSO 1425+6039 has a redshift of $z = 3.18$, so its Lyman alpha emission line peaks at a wavelength $\lambda = (1+z)\lambda_0 = (4.18)(1216\,\text{Å}) = 5080\,\text{Å}$, in the visible range of the spectrum, which makes it convenient for observation (Figure 8.19). The absorption lines from neutral hydrogen in the intervening atomic gas will be at wavelengths ranging from 1215 Å to 5080 Å. For high redshift quasars like QSO 1425+6039, a great many individual absorption lines are seen. The thicket of Lyman alpha absorption lines is referred to as the "Lyman alpha forest". Some of the absorbers along the line of sight are extremely optically thick ($\tau > 10^4$) at the wavelength of Lyman alpha. Therefore, they produce Lyman alpha absorption lines that are saturated in the center and have Lorentz damping wings to either side (see *BA*, sec.6.5). These high density absorbers are called "damped Lyman alpha" systems. Most of the neutral gas in the universe at high redshifts is in damped Lyman alpha systems. By converting part of their gas into stars, damped Lyman alpha systems will evolve into galaxies of the type we see today. The study of Lyman alpha

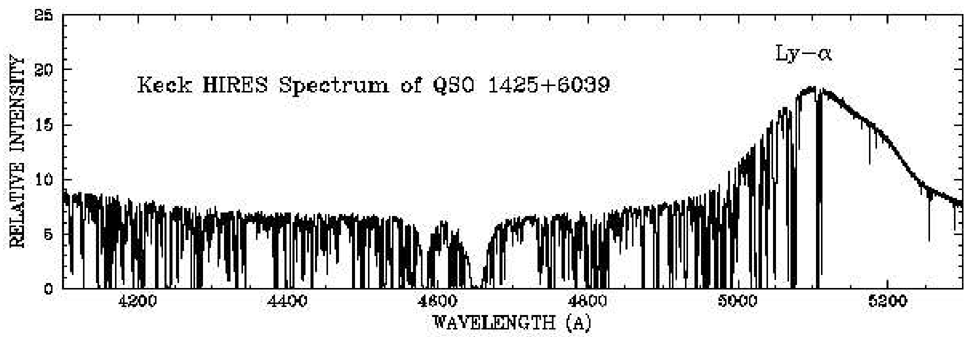

Figure 8.19: Spectrum of the $z = 3.18$ quasar, QSO 1425+6039.

systems is a topic of much interest, since it gives us an unfolding picture of how galaxies and other structures in the universe evolve.