9

Active galactic nuclei and the early history of galaxies

We begin this chapter by discussing galaxies with an *active nucleus*, a compact central region from which we observe substantial radiation that is *not* the light of stars or emission from the gas heated by them. Active nuclei emit strongly over the whole electromagnetic spectrum, including the radio, X-ray, and γ-ray regions where most galaxies hardly radiate at all. The most powerful of them, the quasars, easily outshine their host galaxies. With luminosities exceeding $10^{12} L_\odot$, many are bright enough to be seen most of the way across the observable Universe. But the emitting region may be no bigger than the solar system; its power source is probably the energy released by gas falling into a central black hole. Very luminous active nuclei, such as the quasars, were far more common when the Universe was 20%–40% of its present age than they are today; nuclear activity seems to be characteristic of a galaxy's early life.

In many bright quasars, narrow twin jets are seen to emerge from the nucleus; they are probably launched and kept narrow by strong magnetic fields that build up in the surrounding disk of inflowing matter. In some cases, the jets appear to move outward faster than the speed of light. This is an illusion: the motion is slower than, but close to, light speed. In Section 9.2 we discuss these and similar 'superluminal' jets from stellar-mass objects: microquasars, which are neutron stars and black holes accreting mass from a binary companion, and γ-ray bursts, the final explosion of a very massive star.

In Section 9.3 we consider gas lying between us and a distant galaxy or quasar, which produces absorption lines in its spectrum. Most of the absorbing material is very distant from the quasar, and simply lies along our line of sight to it. The denser gas is probably in the outer parts of galaxies, while the most tenuous material, only a few times denser than the cosmic average, follows the filamentary 'cosmic web' of the dark matter. Surprisingly, this gas is not pristine hydrogen and helium; even when it lies far from any galaxy, it is polluted with the heavy elements which result from nuclear burning in stars.

In the last section of this final chapter, we turn to the question of how today's galaxies grew out of the primeval mixture of hydrogen and helium. Roughly halfway in time back to the Big Bang, galaxies appear fairly normal although starbirth was more vigorous than it is at present. Beyond a redshift $z \sim 2$, they are furiously star-forming, often very dusty, and can no longer be classified according to the scheme of Figure 1.11. The most distant observed systems are seen at $z \sim 6$, less than a gigayear after the Big Bang. New and more sensitive telescopes in the infrared and millimeter-wave regions promise us a much clearer view of the birth of the galaxies.

9.1 Active galactic nuclei

Twinkle, twinkle, little star,
We know exactly what you are:
Nuclear furnace in the sky,
You'll burn to ashes, by and by.

But twinkle, twinkle, quasi-star,
Biggest puzzle from afar;
How unlike the other ones,
Brighter than a trillion suns.
Twinkle, twinkle, quasi-star,
How we wonder what *you* are . . .
after G. Gamow and N. Calder

Many galactic nuclei are very luminous at optical, ultraviolet, and X-ray wavelengths. Others are far dimmer than their host galaxies in these spectral regions, but are strong radio sources. What they have in common is a large energy output from a very small volume, and internal motions that are *relativistic*, with speeds $> 0.1c$ and often much larger.

The optical and ultraviolet spectrum of a quasar typically shows strong broad emission lines characteristic of moderately dense gas (Figure 9.1). The widths of the lines correspond to the Doppler shifts expected from emitting gas travelling at speeds $\sim 10\,000\,\mathrm{km\,s^{-1}}$. These emitting clouds are moving much faster than the galaxy's stars, which typically orbit at a few hundred kilometers per second. Many active nuclei are variable, changing their luminosity substantially within a few months, days, or even hours. The emission lines also strengthen and decline, within a few days or weeks. To allow such fast variability, both broad lines and continuum radiation must come from a region no more than a few light-weeks across.

This tiny volume contains a huge mass. We can use Equation 3.20 to calculate the gravitational force required to prevent the clouds that produce the broad emission lines from escaping out of the nucleus. For velocities $V \sim 10^4\,\mathrm{km\,s^{-1}}$, and radii $r = 0.01$ pc or about two light-weeks, the inferred mass is $\sim 10^8 \mathcal{M}_\odot$. In the nearby radio galaxy M87, we have $\sim 3 \times 10^9 \mathcal{M}_\odot$ within 10 pc of the center

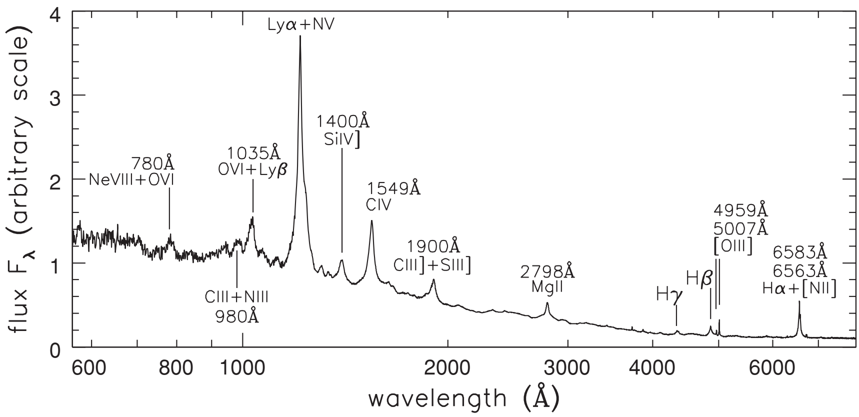

Fig. 9.1. The ultraviolet and optical spectrum of an 'average' radio-quiet quasar – R. Telfer *et al.* 2002 *Ap J* **565,** 773.

(Problem 6.16). The only way to pack the mass of a hundred million suns into a region little bigger than the solar system is as a *black hole*. We then expect the active nucleus to generate its power within a few times the *Schwarzschild radius* R_s. For a mass $\mathcal{M}_{BH}$, this is

$$R_s = \frac{2G\mathcal{M}_{BH}}{c^2} \approx 3 \times \frac{\mathcal{M}_{BH}}{\mathcal{M}_\odot}\,\text{km}. \tag{9.1}$$

Problem 9.1 Show that, for a black hole with the Earth's mass, $R_s \approx 1\,\text{cm}$, whereas if $\mathcal{M}_{BH} = 10^8\mathcal{M}_\odot$, $R_s \approx 2\text{AU}$ or 15 light-minutes. What is R_s for the black hole in the Seyfert galaxy NGC 4258, of Problem 5.15?

Broad emission lines from a galactic nucleus were first reported in 1907, in the early days of galaxy spectroscopy, but no systematic study was made until 1943. Then, Carl Seyfert published a list of 12 galaxies in which the nuclear spectrum showed strong broad emission lines of ions that could be excited only by photons more energetic than those of the young stars that ionize HII regions. These were later divided into the *Seyfert 1* class, with very broad emission lines like those of Figure 9.1, and *Seyfert 2* spectra with lines $\lesssim$1000 km s^{-1} wide. Most of Seyfert's galaxies were spirals, but his list included the huge cD galaxy NGC 1275 at the center of the Perseus cluster of galaxies, which is an elliptical; see Figure 7.9. Table 9.1 shows that 1%–2% of luminous galaxies have Seyfert nuclei.

In the 1950s, as radio astronomy blossomed, many of the strongest radio sources were found to be associated with luminous elliptical galaxies; these are now called *radio galaxies*. In many of these, twin radio-bright lobes, each up to 1 Mpc across, straddle the galaxy. The radio emission is *nonthermal*, produced by energetic particles moving through magnetic fields. For some years, radio

Table 9.1 Densities of normal and active galaxies

Type	*Locally* (Gpc^{-3})	*At $z \sim 1$* (*Gpc^{-3})	$z \sim 2-3$ (*Gpc^{-3})	$z \sim 4$–5 (*Gpc^{-3})
Luminous galaxies: $L > 0.3L_\star$ (Fig. 1.16)	7 000 000	20 000 000		
Lyman break galaxies: $L > 0.3L_\star$			1 000 000	(300 000)
LIRGs: $L_{FIR} > 10^{11}L_\odot$	30 000	3 000 000		
ULIRGs: $L_{FIR} > 10^{12}L_\odot$	<10 000	2 000 000		
Massive galaxies: $L > (2--3)L_\star$	400 000[a]	200 000[b]	(10 000[c])	
Seyfert galaxies	100 000			
Radio galaxies: $L_r > 2 \times 10^8 L_\odot$	1 000			
X-ray AGN: $L_X > 8 \times 10^{10} L_\odot$	100		5 000	
$L_X > 2.5 \times 10^9 L_\odot$	20 000	100 000	30 000	
Quasars: $L > 25L_\star$	90			
$L > 100L_\star$ (Fig. 8.13)	20		600	50
Radio-loud quasars: $L_r > 5 \times 10^8 L_\odot$	4			
$L_r > 3 \times 10^{10} L_\odot$ (Fig. 8.13)	0.004		0.6	0.05

*Densities per *comoving* Gpc^3 with benchmark cosmology; $L_\star \approx 2 \times 10^{10} L_\odot$ from Figure 1.16. Values in ( ) are known to no better than a factor of 3–5.
[a]Local galaxies from 2dF; [b] 'red and dead' galaxies at $z \sim 1.5$; [c] submillimeter-detected galaxies.

astronomers were puzzled by finding some galaxies with radio-bright compact nuclei and others with huge lobes. Better radio maps revealed tiny central cores at the nuclei of radio galaxies, linked to the outer lobes by bright linear jets that carried energy outward.

The first *quasars* (for 'quasi-stellar radio source') were discovered in the following decade, as 'radio galaxies with no galaxy'. They appeared pointlike in optical photographs; only their enormous redshifts betrayed that they were not Galactic stars. Rather, they were gigaparsecs distant, and hence extremely luminous. Subsequently 'radio-quiet' quasars, called *quasi-stellar objects*, or *QSOs*, were found by searching for objects that appeared stellar, but emitted too strongly at infrared or ultraviolet wavelengths relative to their brightness in visible light. Radio-quiet QSOs outnumber radio-loud quasars by at least a factor of 30; both are now believed to be variants of the same type of object, so we use the term 'quasar' to include the QSOs. In the 1980s, deep images of nearby quasars showed us that they were in fact the bright nuclei of galaxies, so luminous as to outshine the surrounding stars. Most astronomers now regard quasars as more powerful versions of a Seyfert nucleus. Quasars cover a very wide range in luminosity: Table 9.1 shows that the most powerful are also the rarest.

BL Lac objects are quasars with very weak emission lines; they may be the most extreme form of active nucleus. They are named after their prototype, which was originally thought to be a variable star, and designated BL Lacertae. The light output of these objects can fluctuate enormously within a few days; one was seen to double its brightness within three hours. Both radio and optical emission are strongly polarized. Quasars with the same pattern of variability, but having stronger emission lines, are called ‘optically violently variable’ (OVV) quasars; these and the BL Lac objects are collectively known as *blazars*. All known blazars are radio-loud. Blazars appear as the most luminous objects in the Universe: if their light were emitted equally in all directions – but see below for reasons why we do not think this is the case – their total output would exceed $10^{14} L_\odot$.

Active nuclei all derive their energy in the same way: gas gives up potential energy as it falls into a black hole. Here, we briefly sketch some of the physical processes involved in turning that energy into the radiation we observe, and explain how a single basic model might explain the diversity observed among active galaxies.

Further reading: B. M. Peterson, 1997, *Active Galactic Nuclei* (Cambridge University Press, Cambridge, UK) reviews the observations. For radio galaxies, see B. F. Burke and F. Graham-Smith, 1997, *An Introduction to Radio Astronomy* (Cambridge University Press, Cambridge, UK). For relevant physics, see M. S. Longair, *High Energy Astrophysics*, 2nd edition: Volume 1, *Particles, Photons and Their Detection* 1992; Volume 2, *Stars, the Galaxy and the Interstellar Medium* 1994 (Cambridge University Press, Cambridge, UK); a graduate-level text is F. H. Shu, 1991, *The Physics of Astrophysics*, Volume 1: *Radiation* (University Science Books, Mill Valley, California).

9.1.1 Seyfert galaxies

Figure 9.2 shows the Seyfert 2 galaxy NGC 4258. In visible light, we see the spiral arms and bright nucleus of a galaxy of type Sbc. The radio map shows emission from bright knots in spiral arms, but also two narrow jets emerging from the nucleus, bending into an ‘S’ shape, and terminating in twin bright lobes on either side of the galaxy. The nucleus is a bright pointlike source in both radio and X-ray bands. The radio emission is strongly polarized, which tells us that it is *synchrotron* radiation, given off as electrons spiral around lines of magnetic field at speeds close to that of light. In this galaxy the radio jets are unusually strong; they overlap with thin helical jets of ionized gas, from which we see emission lines in the optical and ultraviolet. NGC 4258 shows two features common to Seyfert galaxies: radiation that does not appear to originate from stars, and the directed outflow of matter and energy. As we saw in Section 5.5, the nucleus is surrounded by a small disk of fast-rotating gas which we see edge-on; it probably harbors a black hole with a mass exceeding $10^7 \mathcal{M}_\odot$. Seyfert galaxies and quasars shine brightly at infrared, ultraviolet, and X-ray wavelengths, as well as in visible light; but most are not strong radio sources. The quantity νL_ν is roughly constant from the infrared to the X-rays; equal energy is emitted in each interval over which the frequency increases by a factor of ten. The luminosity drops at γ-ray energies, above $\sim$100 keV. Seyfert 2 nuclei tend to be less luminous than the Seyfert 1 nuclei

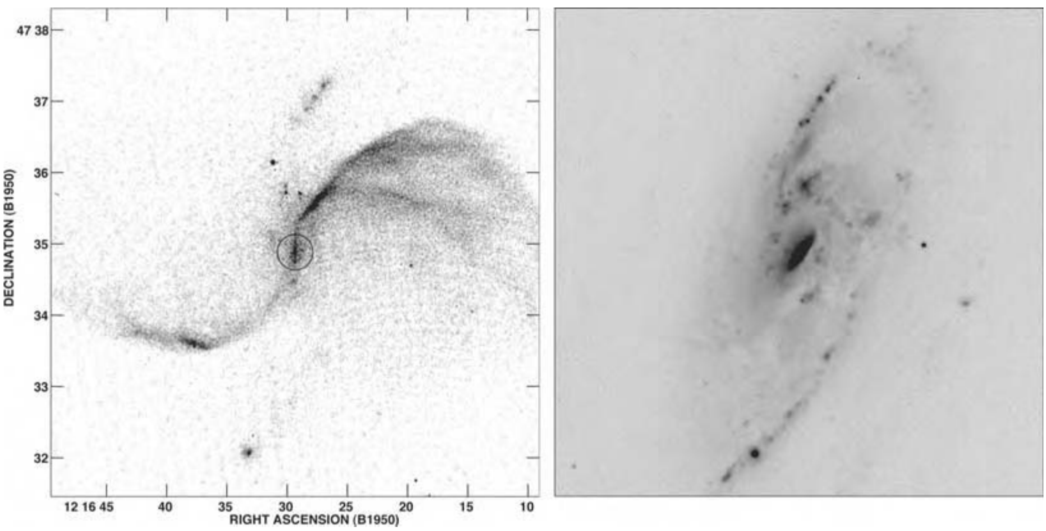

Fig. 9.2. Seyfert 2 galaxy NGC 4258 (Sbc). Left, a radio map at 20 cm shows oppositely directed twin jets (within the circle), channelling radio-bright plasma from the nucleus to lobes at east and west, and HII regions in the spiral arms. Right, an image in the U band at 3700 Å shows the bright center, and brilliant knots of young stars in the spiral arms. At distance $d \approx 7\,$Mpc, $1' = 2\,$kpc – G. Cecil.

in the spectral regions from infrared to soft X-rays, but have similar power in γ-rays. Seyfert nuclei have $M_V \gtrsim -22.5$ or $L \lesssim 10^{11} L_\odot$; more luminous objects would be classified as quasars. The X-ray power ranges from $\sim 2 \times 10^8 L_\odot$ to $10^{11} L_\odot$.

The active nucleus is probably powered by gas that falls into a central black hole. Because it inevitably has some angular momentum, infalling gas forms an *accretion disk*. Viscosity causes the disk gas to spiral slowly inward, heating up and radiating away its gravitational potential energy, until it reaches the last stable orbit around the black hole (see Problem 3.20) and falls in. Theoretically, up to 42% of $\mathcal{M}c^2$, the rest energy of the material, can be extracted from a mass $\mathcal{M}$ falling into a black hole. In practice, astronomers do not expect more than $\sim 0.1\mathcal{M}c^2$ to emerge as radiation. This is still much more efficient than nuclear burning, which releases less than 1% of $\mathcal{M}c^2$. Magnetic fields are pulled inward with the flow of the hot ionized gas. Close to the black hole, the field can become strong enough to channel twin jets of relativistic plasma, moving out along the spin axis at speeds close to that of light.

Some of the infrared flux and all the radio emission comes from particles accelerated to relativistic energies in the jet; paradoxically, we can use long-wavelength radio waves to trace extremely energetic processes. Electrons in the jet scatter some radio or visible-light photons, boosting them to γ-ray energies. The X-ray and ultraviolet emission might come from the hot innermost part of the disk, or from the jet; the visible light probably originates further out in the disk or jet. Additional infrared light may be emitted by surrounding dust grains heated by the nuclear radiation.

The light of a Seyfert nucleus is intense enough to exert considerable pressure on gas around it. If that outward push is too strong, no gas can fall into the center, and the nucleus runs out of fuel. So we have a limit on the luminosity that it could sustain. For a spherically symmetric object, we can calculate at what point radiation pressure just balances the inward force of gravity. We assume that the gas near the nucleus is fully ionized hydrogen, and we calculate the outward force due to Thomson scattering by the electrons; scattering from protons is much less efficient because of their larger mass. The cross-section σ_T of each electron is

$$\sigma_T = \frac{e^4}{6\pi\epsilon_0^2 c^4 m_e^2}\ \text{(SI)}\ \text{ or }\ \frac{8\pi e^4}{3c^4 m_e^2}\ \text{(cgs)} = 6.653 \times 10^{-25}\,\text{cm}^2, \tag{9.2}$$

where e is the charge on the electron and m_e is its mass. If the central source emits photons carrying luminosity L, these have momentum L/c, so an electron at radius r receives momentum $\sigma_T L/(4\pi r^2 c)$ each second.

The electrons cannot move outward unless they take the protons with them; electrostatic forces are strong enough to prevent the positive and negative charges from separating. So we must compare the combined outward force on the proton and the electron with the inward force of gravity on both of them. If the central object has mass $\mathcal{M}$, radiation pressure and gravity balance when

$$\frac{G\mathcal{M}(m_e + m_p)}{r^2} \approx \frac{G\mathcal{M}m_p}{r^2} = \frac{\sigma_T L}{4\pi r^2 c}, \tag{9.3}$$

where m_p is the proton mass. The *Eddington luminosity* L_E is the largest value of L that still allows material to fall inward:

$$L_E = \frac{4\pi G\mathcal{M}m_p c}{\sigma_T} \approx 1.3 \times 10^{31}\frac{\mathcal{M}}{\mathcal{M}_\odot}\,\text{W} \approx 30\,000 \times \frac{\mathcal{M}}{\mathcal{M}_\odot}L_\odot, \tag{9.4}$$

where $L_\odot$ is the Sun's bolometric luminosity of 3.86×10^{26} W. Stars like the Sun come nowhere near the Eddington luminosity, though the brightest supergiants approach it. Although part of the radiation of a Seyfert nucleus comes out in a directed jet, its total luminosity is unlikely to be more than a few times greater than L_E. If $L \sim 10^9 L_\odot$ then Equation 9.4 shows that the central mass must exceed $10^7\mathcal{M}_\odot$, to avoid blowing away all the gas that could fuel the active nucleus.

Problem 9.2 As a mass m of gas falls into a black hole, at most $0.1mc^2$ is likely to emerge as radiation; the rest is swallowed by the black hole. Show that the Eddington luminosity for a black hole of mass $\mathcal{M}$ is equivalent to $2 \times 10^{-9} \mathcal{M} c^2 \, \mathrm{yr}^{-1}$. Explain why we expect the black hole's mass to grow by at least a factor of e every 5×10^7 years.

The spectrum of a Seyfert 1 nucleus is similar to the quasar spectrum shown in Figure 9.1; broad emission lines from a wide range of ions are present. Some of these, such as the Balmer lines of hydrogen and lines of singly ionized species such as MgII, can be excited by ultraviolet photons; they are also seen in the HII regions around hot stars. Others, such as the multiply ionized species NV and OVI, require higher energies. The relative strengths of the various lines can be understood if they are photoionized by radiation from the nucleus; its soft X-rays excite the high-ionization lines.

Figure 9.3 illustrates a basic model for an active nucleus. In the *broad-line region*, gas forms dense clouds with $n_{\mathrm{H}} \gtrsim 10^{10}$ atoms cm^{-3}. From most Seyfert nuclei, we see continuum radiation with wavelengths $\lambda < 912$ Å, shortward of the Lyman limit. These photons would be absorbed if they had to travel through the broad-line emitting gas; so the clouds must cover up only a small fraction of the central source. The emission lines we observe are the sum of Doppler-shifted components from many individual clouds close to the nucleus, each moving at thousands of kilometers per second. As the continuum radiation waxes and wanes, so do the broad emission lines. High-ionization lines follow the continuum with a delay of a few days. Those of low ionization respond later, within a few weeks, showing that they originate further from the nucleus.

The narrow emission lines, such as [OII] at 3727 Å and [OIII] at 5007 Å, come from *forbidden* transitions; see Section 1.2. Forbidden lines are seen only when the density $n_{\mathrm{H}} \lesssim 10^8$ atoms cm^{-3}; at normal laboratory densities, collisions would knock the ion out of its excited state before a photon could be emitted. The forbidden lines of Seyfert galaxies and quasars have widths corresponding to velocities below 1000 km s^{-1}. Forbidden lines have not been observed to vary as the nucleus brightens, indicating that they originate further from the nucleus than the broad lines. The *narrow-line region* is generally a few kiloparsecs across, although in some objects ionized gas has been seen hundreds of kiloparsecs from the center. It is probably a combination of gas glowing in response to the active nucleus and material ionized by massive stars nearby.

Further reading: on the emission-line spectra of active nuclei, see D. E. Osterbrock and G. J. Ferland, 2005, *Astrophysics of Gaseous Nebulae and Active Galactic Nuclei*, 2nd edition (University Science Books, Mill Valley, California).

In Seyfert 2 nuclei, most of the emission lines have roughly the same width, $\lesssim$1000 km s^{-1}. Some strong lines, such as Hα, may show very faint broad wings.

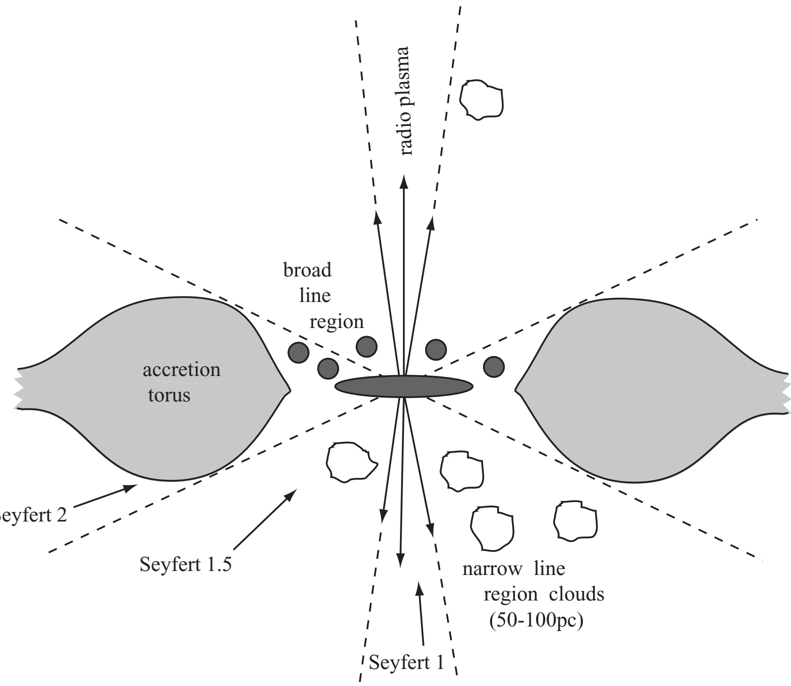

Fig. 9.3. A simple model for an active nucleus. Energetic twin jets emerge at near-light speeds along the spin axis of the central accretion disk. Radiation from the disk and jet photoionizes the dense fast-moving clouds of the broad-line region, which is often $\lesssim$1 pc across. The more diffuse and slower-moving gas of the narrow-line region is at larger radii. Observers looking directly down the jet would see a brilliant Seyfert 1 nucleus; but when it is viewed sideways, through the opaque accretion torus (gray), we have a Seyfert 2 galaxy.

Intermediate classes are used to indicate their strength; a galaxy with fairly weak broad wings might be labelled a Seyfert 1.8 or 1.9. Some Seyfert 2 galaxies, including NGC 4258, have been observed in polarized light: the spectrum then resembles that of a Seyfert 1, with broad emission lines. Reflected light is generally polarized; that is why polaroid sunglasses reduce the glare of light reflected from snow or water. Seyfert 2 galaxies probably have a hidden broad-line region, which we can see only by the reflection of its light in a layer of dust or gas. Figure 9.3 illustrates how a galaxy could appear as either a Seyfert 1 or a Seyfert 2, depending on the viewing angle. This object would be a Seyfert 1 nucleus for observers looking down on the central disk. For those viewing the galaxy close to the plane of the inner disk (as we do for NGC 4258), the continuum source and the broad-line region are hidden by the doughnut-shaped *accretion torus*; they would see a Seyfert 2 nucleus. Because lower-energy X-rays from the nucleus are more easily absorbed by the gas torus, the spectra of Seyfert 2 galaxies show a larger proportion of energetic ‘hard’ X-rays, those with energies above a few keV, than is found in spectra of Seyfert 1 galaxies.

Almost all Seyfert nuclei inhabit spiral or S0 galaxies. Roughly 10% of all Sa and Sb spirals have them, so either all these galaxies spend about 10% of their lives as Seyferts, or one in ten of them has a long-lasting Seyfert nucleus. Most Seyfert galaxies are fairly luminous with $L > 0.3L_\star$, where $L_\star$ of Equation 1.24 represents the luminosity of a sizable galaxy. But NGC 4395, a tiny Sd galaxy with $M_B = -17.1$ or $L_B \sim 10^9 L_\odot \sim 0.05L_\star$, has a Seyfert 1 nucleus. The spectra of Seyfert 2 nuclei often show absorption lines characteristic of hot massive stars; there is a starburst in addition to the nuclear activity.

About 25% of Sa and Sb galaxies have *low-ionization nuclear emission regions*, known as *LINERs*. These are less luminous than Seyfert 2 nuclei, and have spectra with emission lines such as [OI] at 6300 Å and [SII] at 6716 Å and 6731 Å, which do not require high energies for their excitation. The ratios of the line strengths suggest that the gas is ionized as it passes through shock waves. In LINERs [NII] lines at 6548 Å and 6583 Å are normally stronger than Hα, unlike for the galaxies of Figure 5.24. In star-forming systems, [OIII] at 5007 Å is strong relative to Hβ only when [NII]/Hα is weak, while in active nuclei both ratios are normally $>1/3$. In large surveys such as the Sloan Digital Sky Survey and 2dF, we use these ratios to select galaxies with LINER or Seyfert nuclei.

How does the galaxy feed gas into the central black hole? The fuel required is usually less than the mass lost by aging stars in a sizable galaxy. Large quantities of molecular gas, above $10^8\mathcal{M}_\odot$, have been found in the central regions of some nearby Seyfert galaxies. But several nearby disk galaxies, including our Milky Way, have gas at their centers, and nuclear black holes exceeding $10^6\mathcal{M}_\odot$ – with little or no nuclear activity. The presence of dilute gas or stars near the black hole is insufficient to fuel activity. Large concentrations of massive stars could move the interstellar gas around, aiding the accretion. Intense star formation is often found in Seyfert nuclei, supporting this idea. But many radio galaxies conspicuously lack any sign of starbirth.

Problem 9.3 Show that $10^{12}L_\odot$ corresponds to an energy output of $0.1\mathcal{M}_\odot c^2$ per year. As they age, stars like those in the solar neighborhood eject about $\mathcal{M}_\odot$ per year of gas for each $10^{10}L_\odot$ of stars. If all the gas lost by stars in our Galaxy could be funnelled into the center, and 10% of its mass released as energy, how bright would the Milky Way's nucleus be?

9.1.2 Radio galaxies

If our eyes could see in radio wavelengths, many of the brightest objects in the sky would not be within our Milky Way; they would be the luminous active nuclei of galaxies halfway across the Universe. Normal stars, and normal galaxies, are not powerful radio sources. The Milky Way's optical luminosity exceeds $10^{10}L_\odot$; but