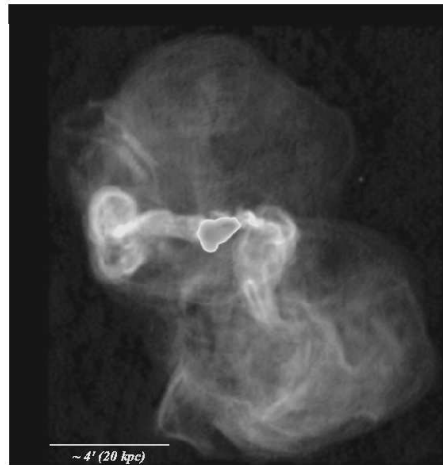


In this section: radio galaxies emit radio waves from regions far outside the visible galaxy, powered by jets of gas emitted from their central regions. The sources seem to be giant black holes formed from millions or even billions of solar masses.

Figure 14.9. Radio emission from M87 is aligned with the jet in the inner region and then spreads out and changes direction. Since the galaxy is more than 10 kpc in radius, or roughly 30 light-years, the large region of emission outside the galaxy indicates that the jet has been active for hundreds of thousands of years. Radio image by Owen, Eilek, and Kassim at the Very Large Array in New Mexico.



If there is new physics to be discovered here, it would not have been found except for the painstaking study of the dynamics of galaxies. We will see a further modern example of how astronomy can be used to discover new physical laws when we discuss the way elements were formed in the Big Bang (Chapter 25).

Radio galaxies: the monster is a giant black hole

When radio telescopes began systematic observations of the heavens in the late 1940s, they soon made completely unexpected discoveries. Astronomers knew that the Sun would emit radio waves, and radio emission from the Milky Way had already been detected. But radio astronomers discovered that many other galaxies were intense sources of radio waves, and that the radio emission was not coming from ordinary stars in these galaxies but from an unknown source associated with the galaxy as a whole.

Radio emission from galaxies is generally associated with jets of gas streaming outwards from a central black hole at nearly the speed of light. Figure 14.9 shows this for the elliptical galaxy M87, which we have seen in previous illustrations. The radio emission comes from a large region surrounding the galaxy, which is coincident with the brightest part of the radio image. In the inner regions it is aligned with the jet we saw in Figure 14.1 on page 164. Notice that the radio emission goes in both directions from the center, which means that there is probably a jet in both directions, even though only one is visible in Figure 14.1. As the jet leaves the galaxy, the radio emission

pattern makes a turn. This could indicate that the jet is running into gas outside the galaxy and is being deflected. The size of the radio lobes indicates that the activity has been taking place for at least hundreds of thousands of years.

These features are absolutely typical of giant radio galaxies. Indeed, M87 is a baby among them: the most luminous ones are thousands of times as bright and ten times the size. Their activity has been going on for millions of years.

What are we to conclude from this? The only mechanism available to a galaxy for maintaining a single direction steady over such a long time is rotation: a rotating disk of gas and/or stars will define an axis of rotation that can normally remain fixed for very long times. Moreover, the dynamical studies of the inner region of M87 indicate that there is a black hole there. Presumably this is not a coincidence.

How does the black hole generate the jets? Where does the energy come from, for example? Nuclear energy is simply not adequate. Consider the numbers: many radio galaxies radiate 10^{38} J s^{-1} in radio waves, which is ten times as much as a typical galaxy radiates in optical light. Yet, as we see in the pictures, the jet originates in a tiny region in the center. No set of nuclear reactions such as we described in Chapter 11 for normal stars could produce this prodigious energy. One has to think of mechanisms for converting the mass of whole stars into energy. The radio luminosity above is the equivalent of converting $1/60^{\text{th}}$ of the mass of the Sun into pure energy every year, using Einstein's famous equation $E = mc^2$, which we will study in the next chapters. And this conversion process must be sustained for millions of

years.

Gravity in relativistic situations offers ways of doing this. A particle falling onto a neutron star reaches it with a speed equal to the escape velocity. We saw in Chapter 12 that the escape velocity from a neutron star is about half the speed of light. Its kinetic energy at this velocity, $mv^2/2$, is therefore a good fraction of its total rest mass energy mc^2 . This energy is in principle available to any processes near the neutron star that could convert it into power for a jet.

In fact, neutron stars are much too small to act as centers for the jet phenomenon. If, say, 20% of the infalling mass is converted into jet energy, the remaining 80% of the mass has to stay near the neutron star, since to send it back out would take as much energy as the mass released by its falling in. If the jet requires the conversion of $1/60^{\text{th}}$ of a solar mass in energy each year, then $1/15^{\text{th}}$ of a solar mass per year must accumulate on the star. After only something like 15 years, this would push the neutron star over the upper mass limit and convert it into a black hole. Over a few million years, at least $10^5 M_{\odot}$ will have accumulated in the region where the jet originates. Therefore, the mechanism needs a massive central black hole for its relativistic gravitational field. Astronomers call this massive black hole “the monster”.

Other possibilities have been proposed: supermassive relativistic stars, extremely dense clusters of neutron stars, and others. It seems, however, that even if one could somehow form such systems, they would not last long before collapsing to form a massive black hole. The conclusion that the monster is a massive black hole seems inescapable.

Quasars: feeding the monster

The discovery of the enormous luminosity of quasars in 1963 by the Dutch astronomer Maarten Schmidt (b. 1929) was a landmark in the development of modern astronomy. Radio astronomers had identified a class of unusual, intense radio sources that did not seem to be associated with galaxies. Optical observations revealed point-like images at the positions of some of the radio sources, but the images were not like ordinary stars. In particular, their spectra did not look like spectra of stars, and in fact no-one could identify any of the lines. They were called *quasi-stellar objects*, a name that has evolved into *quasar*, and is frequently abbreviated QSO.

Schmidt decided to see if he could interpret the spectrum of one of these objects, called 3C273, by applying a very large Doppler shift to some standard spectral lines of hydrogen. He found that he could indeed fit the spectrum of 3C273, provided he used a shift corresponding to a recessional velocity of 15% of the speed of light. This was far larger than any velocity that had by then been measured for galaxies. Interpreted as a Hubble velocity, it meant that 3C273 was one of the most distant objects known. Although it looked like a dim star on photographic plates, its great distance meant that it was actually one of the most luminous objects known.

The redshifts of other quasars were soon measured, and a number of features emerged. First, quasars put out much more light than an ordinary galaxy, so it is likely that they are associated with some phenomenon that takes place in the center of some galaxies, like that which produces radio galaxies. Second, most quasars are so far away that the light we see has been traveling to us from them for a good fraction of the time since the Big Bang. The Universe was younger then, and it is natural to conclude that quasars have something to do with the early stages of the formation of their “host” galaxies. Third, quasars were much more numerous in the early Universe than they are now. They were so numerous that a sizeable fraction of galaxies must have had quasars in them at one time, although in our Galaxy’s

In this section: quasars also seem to contain black holes, and they give a clue to the source of the energy: gas falling towards the black hole.

▷Initially there was some skepticism that the enormous quasar velocities should be interpreted as part of the Hubble expansion. But very sensitive optical observations have revealed many quasars in clusters of normal-looking galaxies of the same redshift. There can therefore be no doubt about the enormous distances to these objects, and hence their enormous luminosities.