The real voyage of discovery lies not in seeking new landscapes but in having new eyes.

--Marcel Proust

The sciences do not try to explain, they hardly even try to interpret, they mainly make models. By a model is meant a mathematical construct which, with the addition of certain verbal interpretations, describes observed phenomena. The justification of such a mathematical construct is solely and precisely that it is expected to work.

--John von Neumann

Chapter Preview
It takes one billion years for light to travel from a galaxy one billion light years distant to the Earth. By photographing a galaxy at a distance of one billion light years we obtain a picture of it as it was one billion years ago, not as it is now. As we look farther and farther out into space we look further back in time. By taking snap-shots of galaxies at increasing distances we can look at the evolutionary paths that galaxies have taken over time, not for any individual galaxy, but for galaxies in general. When we do this we see that in epochs past galaxies were not the same as they are now, but were significantly more luminous. Some exhibited violently explosive events in their nuclei, so energetic that they nearly defy explanation. In this chapter we will examine these active galaxies and review the current theories of their central energy sources.

**Key Physical Concepts to Understand:** non-thermal emission of radiation, properties of radio galaxies, Seyfert galaxies, BL Lacertae objects, and quasars, determination of the maximum size of a
radiation source from its variability, models of the energy source(s) for active galaxies

I. Introduction

- Radio astronomy was born in 1931 when Karl Jansky of Bell Telephone Laboratory discovered radio emission from our Milky Way Galaxy.
- In 1939 Grote Reber, a radio engineer, built his own backyard radio antenna and began his hobby as an amateur radio astronomer (Figure 1).
- He built his 31-foot radio dish for a cost of about $1,300, and for several years was the only practicing radio astronomer in the world.
1. Early radio astronomy began to flourish in England and Australia shortly after World War II.
2. Hundreds of radio sources were discovered, many of which were found to correspond to optically visible counterparts.

Figure 1. Photo of Grote Reber’s radio telescope, in his backyard in Wheaton, IL.
3. Some were associated with supernova remnants and peculiar galaxies.
4. Some radio-emitting galaxies manifested evidence of explosive violence, such as extremely high luminosities and the ejection of large masses of gas at high velocity (Figure 2).
5. It was previously thought that galaxies were basically quiescent, although every one hundred years or so an individual star in a galaxy might supernova.
6. With the era of radio astronomy began discoveries of galaxy luminosity variability over short time periods, violent events in galaxy nuclei, and galaxies of implausibly high luminosities. We call these active galaxies.
Figure 2. The violent expulsion of matter from the center of the galaxy M87 appears to be an elliptical galaxy with a large jet of gas being expelled from its nucleus at a significant fraction of the speed of light. The resulting radio emission makes M87 one of the brightest galaxies in the radio
part of the spectrum. Its radio source designation is Virgo A. P 567-31.40?

- Normal galaxies like the Milky Way emit only a small fraction of their total energy output in the radio.
- The luminosity of the Milky Way is the sum of the near-blackbody emission of its stars, peaking in the visible.
- Because it is the sum of a group of blackbodies astronomers call it thermal emission (Figure 3).
- Emission that does not approximate a blackbody or a group of blackbodies is called non-thermal emission.
- Radio-emitting active galaxies are mostly non-thermal in their electromagnetic spectra, with a brightness that remains constant or even increases towards longer wavelengths (Figure 3).
- Non-thermal emission is usually associated with the radiation from fast electrons gripped in spiral trajectories by a strong magnetic field (Figure 4).
• This emission is called **synchrotron emission** because it is observed in high energy particle accelerators of the same name.
• Synchrotron emission occurs near the Earth’s magnetic poles in aurorae when solar particles spiral along the Earth’s magnetic field.
• High luminosity non-thermal emission is a signature characteristic of active galaxies.
Figure 3. Non-thermal emission from a quasar and thermal emission from a quasar.

![Figure 3. Non-thermal emission from a quasar and thermal emission from a quasar.](image)

Figure 4. Electrons spiraling around lines of magnetic force give rise to the synchrotron emission of electromagnetic radiation. P 523-30.6.

1. Imagine a cube 300 million light-years on a side, centered on the Milky Way (Figure 5).
2. Inside the imaginary 300 million light-year cube galaxies are usually normal spiral and elliptical galaxies with thermal emission spectra.
3. However, outside this cube we see many galaxies that do not fit this profile because they
are active galaxies; they are highly luminous, their luminosity varies with a time-scale of days to years, and they exhibit a non-thermal emission spectrum with unusually strong radio emission.

4. Many of these active galaxies exhibit most of their luminosity from an almost unbelievably small central region.

5. Active galaxies are commonly classified into a number of groups according to their characteristics: radio galaxies, Seyfert galaxies, BL Lacertae objects, and quasars.

How are the distances to these galaxies determined? It is generally assumed that the measured red shifts of galaxies are a result of the expansion of the Universe; their distances are determined from their measured red shifts and the Hubble relation.

II. Nearby Radio Galaxies
The Milky Way, like any normal (non-active) galaxy is radio quiet.

Its thermal emission peaks in the visible and decreases steadily toward longer wavelengths.

As a result it emits only roughly 0.1% of its luminosity in the radio portion of the spectrum.

Nearby radio loud galaxies can be divided into two types: core-halo radio galaxies and double-lobed radio galaxies.

A. Core-Halo Radio Galaxy

1. Core-halo galaxies are elliptical in shape with emission from a small central core, perhaps 1 light year across.
2. The core has a luminosity as high as $10^{50}$ ergs/s, a million times greater than the total luminosity of the Milky Way.
3. Weak radio emission can sometimes be detected from the 100,000 light year diameter halo, roughly the size of the Milky Way.
4. Most core-halo galaxies are faint in the visible portion of the spectrum.

M87 is a typical core-halo galaxy only 50 million light years distant (Figure 2). M87 would be classified as an elliptical galaxy but for a thin jet of gas emanating from its core; as a result it is classified as a peculiar galaxy. M87 is roughly 100,000 light years across, as is the Milky Way. The gas jet is 5,000 light years long travelling at 25,000 km/s (nearly one-tenth the speed of light) as measured from the Doppler shift of the emission lines originating in the gas.

Characteristics of Core-halo galaxies include:

- A small non-thermal core (less than several light years across)
- Highly luminous non-thermal emission (a million times the luminosity of the Milky Way)
- Often associated with weak elliptical galaxies
- High velocity ejection of gas from the nucleus (up to a significant fraction of the speed of light.)
B. Double-Lobed Radio Galaxy

A typical example of a double-lobed radio galaxy is Centaurus A, an elliptical galaxy 15 million light years distant (Figure 7).

Centaurus A is 100,000 light years across and would be classified as an elliptical galaxy if not for the chaotic dust lane that bisects it; the dust may have resulted from an explosion in its nucleus. As a result it is classified as a peculiar galaxy. Radio emission is only weakly detected from the optical counterpart of this galaxy. Most all of the radio emission occurs from its extended lobes. Each lobe is about 400,000 light years across, much bigger than a typical galaxy. If a line were drawn connecting the two lobes, the visible galaxy would be precisely in line with the radio lobes and halfway between them.

Centaurus A is 3 million light years across from end to end, as large as our Local Group of galaxies is.

Some double-lobed radio galaxies are even larger, up to 10 million light years end-to-end (Figure 8), representing the largest single galaxies observed.

A second smaller and weaker set of lobes, each 50,000 light-years in diameter, is seen interior to the large lobes in Centaurus A.
Figure 7. Panel A: The double-lobed radio Galaxy Centaurus A. In visible light (Panel A), near infrared (Panel B showing a galaxy that Cen A absorbed a half-billion years ago), far infrared (Panel C showing thermal emission from dust), radio (from synchrotron radiation, Panel D), and X-rays (from synchrotron radiation, Panel E) and Panel F. A false-color with radio in red, infrared in green, and X-ray in blue. Panel G shows the size of Cen A on
the sky compared with the full moon, along with radio telescopes at CSIRO in Australia.

Characteristics of double-lobed radio galaxies:

- No core radiation in the radio (an optical counterpart is often seen precisely midway between the radio lobes).
- The galaxies are enormous. (The lobes are up to 10 million light years across.)
- Luminosities up to $10^{52}$ ergs/s (100 million times the luminosity of the Milky Way), almost all in the radio.
What makes these double-lobed radio galaxies tick? What causes their double-lobed appearance? What energy source drives their fantastic luminosities? It is thought that some incredible astrophysical "engine" at the center of the double-lobed radio galaxies injects electrons in two opposite directions along magnetic fields at near the speed of light. After the electrons have traveled millions of light years they slow down as they plow through the gas that exists between galaxies. In decelerating they generate radio radiation (synchrotron radiation, which is emitted by accelerating or decelerating electrons). The result is radio emission from double lobed sources, among the brightest radio sources in the sky. The central engine that drives active galaxies in general and double-lobed radio galaxies in particular could be a supermassive black hole residing the galaxy nucleus. We will review this in Section V.

III. Active Galaxies at Intermediate Distances: Seyfert Galaxies and BL Lac Objects

A. Seyfert Galaxies
• Seyfert galaxies are a type of active galaxy, named after their discoverer, the American astronomer Carl Seyfert.
• Seyfert galaxies resemble normal spiral galaxies, but have superluminous nuclei with one hundred times more radio, infrared and x-ray luminosity than normal galaxies (Figure 9).
• Although the Milky Way galaxy has non-thermal emission originating in its nucleus, it is only a small fraction of its total energy output, roughly 1%.
• With a core luminosity of $10^{46}$ ergs/s, Seyfert nuclei can be a million times more luminous than the center of our own galaxy.
• Doppler velocity measurements from spectroscopy of Seyfert nuclei reveal clouds of hot gas ejected at high velocities, 1,000 km/s. This gas has similar emission lines as the center of the Milky Way.
• The Seyfert galaxy phenomenon may represent a few percent of all spiral galaxies.
• Seyfert nuclei are variable, the luminosity changing by a factor of 2 within a year.
• High-resolution radio maps confirm that this variability originates from an incredibly small
region at the galaxy center, not much larger than the Oort comet cloud surrounding our Solar System.

- Astronomers suspect that violent explosions are the culprits that cause Seyfert nuclei variability, high-intensity bursts of energy emanating from the compact nucleus.
- Similar events are seen in the Milky Way, but Seyfert events are literally one million times more dramatic.

Characteristics of Seyfert galaxies:

- 3-5 billion light years distant
- a typical spiral with an active nucleus.
- nuclear gases moving at 1,000 km/sec
- a nucleus one million times brighter than the Milky Way nucleus, 100 times brighter than the entire Milky Way
- radio and infrared radiation is strong, as is X-ray emission
- variable on a time scale of a year
• Is a Seyfert galaxy a phase in every spiral galaxy’s evolution or a classification of a small percentage of galaxies?

• Seyfert galaxies represent 2-5% of all galaxies seen at near to moderate distances. Does this mean that only a small percentage of all spiral galaxies go through this phase? No. When shopping at the mall you might notice that only a small percentage of women are obviously pregnant. This does not mean that only a small percentage of women ever bear children, it just means that the latter stages of pregnancy are short compared to the mean lifetime of a woman. The Seyfert galaxy phase might be a relatively short phase in the life of a spiral galaxy when its nucleus becomes extremely active.

• The same principle may apply to all types of active galaxies.
Figure 9. The Seyfert galaxy NGC 1566. This galaxy appears to be a normal spiral except for its unusually bright nucleus, which varies on a time scale of weeks. Wikipedia.

B. BL Lac Objects

BL Lacertae Objects are named for their prototype galaxy in the constellation Lacertae (the lizard), originally thought to be a variable star (Figure 10). They are similar to Seyfert galaxies in some respects: they have a superluminous nucleus at all wavelengths, with rapid variations in brightness.

BL Lac objects appear to have an underlying elliptical galaxy whereas Seyfert galaxies have an underlying spiral galaxy.
IV. Quasi-Stellar Radio Sources

- In the 1960s dozens of radio sources were identified with optical galaxies; many were associated with elliptical galaxies. One of these was 3C 48, the 48th radio source in the 3rd Cambridge catalog of radio sources. 3C 48 didn’t look extended like a galaxy but appeared point-like, as a star. Many astronomers thought that it was a radio-emitting star.
- Other radio sources were also discovered that were later identified with objects that appeared to be unusually blue, faint stars on visible wavelength photographs.
• These were later called quasi-stellar radio sources, or quasars for short (Figure 11).
• Optical spectroscopy revealed emission lines at wavelengths that did not correspond to known atoms. In 1963, Martin Schmidt of Mount Wilson studied four emission lines in a radio source called 3C 273.
• He found these lines made physical sense if he assumed that they came from four hydrogen lines red shifted at 14.5% of the speed of light.
• Now all quasars can be explained as emission from gas of ordinary composition at unusually high velocities, some at more than 90% of the speed of light.
• It was discovered that not all high red shifted point-like galaxies are radio sources, but the name stuck. All high red shift quasi-stellar galaxies are now called quasars, radio loud or not.
• There are currently approximately 8,000 galaxies classified as quasars, approximately one out of every 1,000 galaxies. Again, the question is "Is a quasar a short phase through which every galaxy passes, or is it a rare type of galaxy?"
Quasar Host Galaxies

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J. Bahcall (Institute for Advanced Study), M. Disney (University of Wales) and NASA
Figure 11. **Panel A:** An image of the quasar 3C 273 taken with the Hale Observatory 200-inch telescope. Notice the jet of material emanating from the point-like quasar. **P 580-32.1.** **Panel B:** The red shift in the spectrum of 3C 273. The lower spectrum is the spectrum of hydrogen and helium in a calibration source at the telescope. The upper spectrum is that of the quasar, taken through the same instrument. Three hydrogen Balmer lines are labeled on both spectra. Note how far to the red (right) the quasar’s hydrogen lines have been displaced. **P 581-32.3** **Panel C:** 3C 273 in a cluster of galaxies at the same red shift. The bright object marked "Q" is the quasar. The numbered objects are galaxies with the same red shift as the quasar. Note how much brighter the quasar is than the other galaxies. **P 590-32.14.** **Panel B,** Quasars seen surrounded by spiral and elliptical galaxy hosts.

- Quasars exhibit the largest red shifts of any astronomical objects; some appear to be moving at more than 90% of the speed of light. This red
shift is interpreted as being cosmological due to the expansion of the Universe.

- This interpretation allows astronomers to calculate a quasar’s distance from its red shift.

Normally quasars are seen at distances of 6-13 billion light years, with the most distant quasars seen with velocities of 95% of the speed of light.

**Calculating quasar distances from their red shifts results in two conclusions:**

1. **Quasars are the most distant galaxies in the Universe; some are as far away as 10-billion light years. At this look-back time, we are seeing the initial epoch of galaxy formation after the Universe was created.**

2. **Although quasars appear to be faint, their intrinsic luminosities must be incredibly high for us to be able to see them at these distances. They have luminosities one thousand to one billion times the luminosity of the Milky Way. The represent the most luminous galaxies that we can see.**
The source of radiation in a quasar is no bigger than one light year!

Quasars are even more amazing when we calculate the size of the region in a quasar that is generating this enormous energy. Quasars exhibit large luminosity variations on time scales of weeks and sometimes days. The time scale of such a variation can be linked directly to the size of the emitting region. Think of being able to instantaneously turn off and on the power to the Sun, if this were possible, in such a way that all of the Sun’s photosphere became dark at one moment in time and became bright at another moment (Figure 12). The Sun’s radius is approximately 4 light-seconds. If the Sun were switched off, 8 minutes afterwards, the light travel time between the Sun and Earth, the center of the Sun’s disk would go dark, but light from the edge of the Sun would continue to arrive for 4 more seconds, since it is 4 light-seconds more distant than the center of the disk. Instead of the Sun appearing to instantly switch off, its intensity would decay over 4-seconds, half of the light
travel time from the nearest side of the Sun to the farthest side. If the Sun were instantly switched back on, it would take 4 seconds for the Sun to increase in brightness, from the time that the center appeared bright to the moment of full solar brightness. The relationship between the size of an object and its time scale for variability is illustrated in Table 23.1.

**Quasar Variability and Size**

![](image)

**Variability of the Quasar 3C279 from Harvard Survey Plates by Eachus & Liller**
The large distances and extreme brightness of the quasars implies tremendous energy output; how do they do that? The question was complicated by the discovery that quasars vary in brightness, sometimes by huge amounts in periods as small as a week or so. There is a simple argument that the size of a variable, luminous object cannot be larger than the distance that light travels during its time of variation (i.e. if an object varies significantly in brightness over a period of a week, it cannot be larger than a light-week in size.)
Figure 12. Variability of quasars relates to the size of the energy source. If a 1-light week radius source and a 1 light-year radius source are turned on abruptly, it takes 1 week for the small object to appear to come up to full intensity and 1 year for the larger object. Similarly, if both are turned off abruptly, the larger object experiences 1 year of decreasing intensity, the smaller object 1 week. From http://casswww.ucsd.edu/archive/public/tutorial/Quasars.html
In quasars the time scale for significant luminosity variations places a limit on the maximum size of the emitting region. For example, if a quasar doubles its luminosity in a period of 1 day, then 50% of the emission from the quasar must be coming from a volume no larger than about one light-day across, approximately the size of our Solar System out to twice the distance of the orbit of Pluto. For many quasars this would imply an energy output of 100 trillion solar luminosities squeezed into a volume the size of the Solar System.

**Table 23.1:** Estimating the Size of an Object from its Variability Time Scale

<table>
<thead>
<tr>
<th>Variability Time Scale</th>
<th>Maximum Size of Emitting Region (km)</th>
<th>Object of Similar Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01 seconds</td>
<td>3000</td>
<td>Moon</td>
</tr>
<tr>
<td>Time</td>
<td>Luminosity</td>
<td>Space Event</td>
</tr>
<tr>
<td>--------------</td>
<td>-------------</td>
<td>--------------------------</td>
</tr>
<tr>
<td>1 second</td>
<td>$3.0 \times 10^5$</td>
<td>Moon’s Orbit</td>
</tr>
<tr>
<td>5 seconds</td>
<td>$1.5 \times 10^6$</td>
<td>Sun</td>
</tr>
<tr>
<td>8.3 minutes</td>
<td>$1.5 \times 10^8$</td>
<td>Earth’s Orbit</td>
</tr>
<tr>
<td>1 hour</td>
<td>$1.8 \times 10^9$</td>
<td>Jupiter’s Orbit</td>
</tr>
<tr>
<td>1 day</td>
<td>$2.6 \times 10^{10}$</td>
<td></td>
</tr>
<tr>
<td>1 week</td>
<td>$1.8 \times 10^{11}$</td>
<td></td>
</tr>
<tr>
<td>1 year</td>
<td>$9.5 \times 10^{12}$</td>
<td>Oort comet cloud</td>
</tr>
</tbody>
</table>

- In the years after the discovery of quasars, astronomers were not entirely happy with the idea that there were galaxies whose energy sources were a billion times more luminous than the whole of the Milky Way.
- After all, there were no satisfactory models for this luminosity.
• Alternative models were suggested that placed quasars nearby, in the neighborhood of the Milky Way. This would make it easy to explain their apparent brightness. One suggestion had them as objects being ejected from the nucleus of our Milky Way. Another attributed their enormous red shifts as gravitational red shifts of local objects.

• Observations in the last ten years have proved beyond a shadow of a doubt that quasars are not local objects, and in fact are at the distances suggested by their red shifts.

• This evidence includes gravitational lensing, a general relativistic effect, of a quasar by a more nearby galaxy, resulting in multiple images of the quasar (Figure 13).

• and the detection of faint galaxies in the same cluster as "normal" galaxies, all at the same red-shift (Figure 11c). High sensitivity images of quasars in many cases show an extended nebulosity, reminiscent of the outer portion of a typical faint galaxy.
Figure 13. Gravitational lensing of a quasar. This peculiar object, called an Einstein cross, provides verification of the General Theory of Relativity and the great distance of quasars. The four bright objects are actually four copies of a single quasar, 8 billion light years away, lensed by the surrounding fuzz, a foreground elliptical galaxy at a distance of 400 million light years. **FMW 532-26.20a? APOD.**

One of the most distant quasars is the radio source 3C275.1, with a red shift corresponding to a distance of 7 billion light years. **Figure 14** shows that this
quasar is not very remarkable in appearance, looking like a fuzzy star, but we probably shouldn’t expect such a distant object to look otherwise.

Figure 14. A Hubble Telescope Image of the underlying galaxy around the quasar QSO 1229 +204. On the right is an artist’s concept of a quasar. FMW 523-26.6.

Characteristics of quasars:

- faint but luminous
- all distant (4-13 billion light years away)
- variation in luminosity over 1 light-day (indicating the source of luminosity is less than one light-day across)
IV. The Central Engines of Active Galaxies: a Supermassive Black Hole?

What makes quasars tick? Where does this energy come from? If a quasar is 1 million times more luminous than a normal galaxy then does it have 1 million times more stars? One difficulty in modeling the intense luminosity of active galaxies is estimating the lifetime over which that luminosity is maintained. This can be illustrated by using a supernova as an example. A supernova with a peak luminosity of \(10^{44}\) ergs/sec can outshine an entire galaxy for a time scale of a year or so (roughly \(10^7\) seconds). But its total energy output is equal to its luminosity (the amount of energy radiated per unit time) times its lifetime. A supernova has a very intense, but very short lifetime. Using equation 23.1
one can calculate the total amount of energy that it will radiate:

\[10^{44} \text{ ergs} \times 10^7 \text{ seconds} = 10^{51} \text{ ergs}\]. This is only about ten times the amount of energy radiated by the Sun over its lifetime, because the Sun will have a much greater longevity than a supernova.

A high luminosity quasar has an energy output of \(10^{52}\) ergs/s. To power it with conventional one solar mass stars would require \(10^{19}\) stars, equivalent to 100 billion Milky Way galaxies, all packed into a region the size of the Solar System.

No objects in the Universe with anywhere close to this mass range are thought to exist. Stars are not the most efficient way of generating energy since only 0.7% of the mass of hydrogen is converted to energy when it fuses into helium, and only the inner 10% of a one solar mass star fuses hydrogen, for an overall efficiency of less than 0.1%. But the Sun produces energy for 10 billion years. We don’t really know how long an active galaxy remains active. We must compare the total amount of energy generated by stars like the Sun with the total amount of energy
expected to be generated over the lifetime of an active galaxy. This total energy is given by equation 23.1. Comparisons of the total energy output of the Sun, a 1 megaton nuclear bomb, and the Milky Way are given below:

\[ \text{Equation 23.1: Energy} = \text{Luminosity} \times \text{Lifetime} \]
\[ (1 \text{ watt} = 10^7 \text{ ergs/sec}) \]

- **Nuclear Explosion (1 megaton)**
  \[
  \text{Luminosity} = 10^{23} \text{ ergs/sec} \\
  \times 10^{-6} \text{ sec duration} \\
  = 10^{17} \text{ ergs (for comparison } 10^7 \text{ ergs/sec} = 1 \text{ watt})
  \]

- **Sun**
  \[
  \text{Luminosity} = 10^{33} \text{ ergs/sec} \\
  \times 10^{17} \text{ sec lifetime} \\
  = 10^{50} \text{ ergs}
  \]
• **Milky Way**

Luminosity = \(10^{11}\) stars \(\times 10^{33}\) ergs/sec/star = \(10^{44}\) ergs/sec

\[\times 10^{17}\text{ sec lifetime}\]

\[= 10^{61}\text{ ergs}\]

**Table 23.1: Energy Output of Normal & Active Galaxies**

<table>
<thead>
<tr>
<th>Object</th>
<th>Luminosity (ergs/s)</th>
<th>Total Energy Over Objects Lifetime (ergs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nuclear Bomb</td>
<td>(10^{23})</td>
<td>(10^{17})</td>
</tr>
<tr>
<td>Sun</td>
<td>(10^{33})</td>
<td>(10^{50})</td>
</tr>
<tr>
<td>Supernova</td>
<td>(10^{44})</td>
<td>(10^{51})</td>
</tr>
<tr>
<td>Black hole candidates have been found at the centers of the nearby galaxies M31 (Andromeda), M32, M104, and M87, as well as our own Milky Way. Spectroscopic red shift measurements of the core of M31, for example, show that stars within 50 light years of the center are orbiting at speeds which from</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Kepler’s 3rd law indicate 50 million solar masses inside this radius (Figure 15). Such a large mass density would suggest the presence of a supermassive black hole.

Figure 15. *Black hole at the center of M31.*

Recent Hubble Space Telescope images show M87 (Figure 16) to be a double-lobed elliptical galaxy with a bright disk at its center, trailing spiral arms of matter from an exceptionally bright nucleus. It is thought (from what?) that we are viewing a 3 billion solar mass black hole and its accretion disk.
Figure 16. Evidence of a black hole at the center of the galaxy M87. To the left are Doppler-shifted emission lines from the opposite sides of the disk at the core of M87. The large Doppler shifts indicate that a disk of dust and gas is rotating at a velocity of 550 km/s, indicating that gas is orbiting a supermassive object. FMW 527-26.13.

It is not unexpected that supermassive black holes would be common at the centers of galaxy nuclei.
Although no one has indisputably identified even a single nearby black hole, evidence for their existence is strong (Chapter 20, Section IV). And while a 10 solar mass black hole is unbelievably dense: $10^{36}$ kg/m$^3$, the densities of black holes drop with increasing mass. A 1 billion solar mass black hole would only have a density of 1% of that of water. Moreover it is logical to expect that during the collapse of a galaxy-forming cloud of gas and dust an enormous amount of matter would eventually gravitate (literally) to the center of mass of a galaxy, eventually achieving a high enough density to form a supermassive black hole.

Black holes, if common at galaxy centers, could explain active galaxies. As in accretion disks around lower mass black holes (Chapter 20, Section IV), infalling matter is expected to form a bottleneck near the black hole event horizon, forming a spinning disk of dust and gas (Figure 17). As matter spirals towards the black hole its density increases. The orbital velocity of matter increases as one approaches the event horizon. Friction occurs between particles as they collide with each other at
high velocity. This friction heats the accretion disk, which radiates energy throughout the electromagnetic spectrum. This conversion of gravitational potential energy to light is much more efficient than the production of energy by nuclear fusion. **The luminosity produced by infalling mass converted to energy can account for the luminosity of a quasar with only about 30 solar masses of infalling material per year.**
Figure 17. A painting of a black hole and its accretion disk, with two beams of matter being ejected from a region just outside the Schwarzschild radius. FMW 530-26.16.

Not all of the infalling matter would move through the event horizon. Ultra-high temperatures in the inner part of the accretion disk create an intense pressure that sends an expanding gas through the only path that is not blocked by infalling matter, up through the poles of the accretion disk, forming opposite jets of high velocity particles. Similar to the pulsar model, two beams of accelerating particles are expelled that will produce intense synchrotron radiation when they are slowed.

Why is matter ejected in narrow jets? It is thought that ejected mass is forced into narrow beams by the infalling material which spirals into the black hole in an accretion disk. The expelled material might also be focused by a magnetic field, so that charged particles follow the polar magnetic field lines, as has been modeled for pulsars (Chapter 19, Section VI).
What evidence is there of an accretion disk in a galaxy nucleus? Hubble Space Telescope images of galaxy nuclei show evidence of intense central emission in M51 as well as the galaxies M32, M87, and M104, mentioned above. M51 (Figure 18) shows an edge-on dust disk that bisects lobes of visible and radio emission. The disk is seen to be about 100 light years in diameter.

Figure 18. *Hubble image of the core of M51.*
• How can the supermassive black hole accretion disk explain active galaxies?
• Nearby radio galaxies are seen either as double-lobed sources or core-halo sources. The difference might simply be an effect of viewing geometry.
• A radio source seen with its accretion disk edge-on would exhibit two lobes of radiation from the material exiting the twin poles of the supermassive black hole (Figure 19).
• A radio source seen face-on would appear as a core-halo source as we would view only the end of a single high-energy jet.
Observed Properties of Jets and the Angle to the Line of Sight $\theta$

<table>
<thead>
<tr>
<th>Host Galaxy</th>
<th>AGN</th>
<th>Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>90 deg</td>
</tr>
<tr>
<td></td>
<td></td>
<td>60 deg</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30 deg</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0 deg</td>
</tr>
</tbody>
</table>
What about Seyfert galaxies, BL Lac Objects, and quasars? The difference between active galaxies of different types may be evolutionary. Quasars are seen only at great distances, Seyfert galaxies and BL Lac Objects are seen primarily
at intermediate distances, and "normal" galaxies and radio galaxies dominate space within several hundred million light years.

- This would seem to indicate that in the initial epoch of galaxy formation, galaxy nuclei looked like quasars, perhaps due to the infall of relatively large amounts of material into galaxies’ central black hole.
- The net result was a super-luminous core. As galaxies evolved over billions of years this infall rate would be expected to level off and slow down, producing less luminous cores.
- When the core is seen at the center of a spiral galaxy we might have a Seyfert galaxy, when seen at the center of an underlying elliptical galaxy we might have a BL Lacertae object.
- When galaxies continue to evolve and the black hole mass infall rate continues to decline we might expect to see active galaxy cores of more limited luminosities, ordinary radio galaxies and typical galaxies like the Milky Way.
- This scenario is a popular but speculative hand-waving model of active galaxies. Real physical
models await more data and much more computer modeling by theorists.

These galaxies can be broadly summarised by the following table:

<table>
<thead>
<tr>
<th>Active Nuclei</th>
<th>Emission Lines</th>
<th>X-rays</th>
<th>Excess of UV</th>
<th>Excess of Far-IR</th>
<th>Strong Radio</th>
<th>Jets</th>
<th>Variable</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Narrow</td>
<td>Broad</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>I</strong></td>
<td>no</td>
<td>weak</td>
<td>none</td>
<td>weak</td>
<td>none</td>
<td>none</td>
<td>no</td>
</tr>
<tr>
<td><strong>Seyfert I</strong></td>
<td>no</td>
<td>yes</td>
<td>no</td>
<td>some</td>
<td>no</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td></td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>some</td>
<td>some</td>
<td>yes</td>
<td>few</td>
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<tr>
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<td>yes</td>
<td>yes</td>
<td>no</td>
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<td>some</td>
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<td>yes</td>
</tr>
<tr>
<td></td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>some</td>
<td>yes</td>
<td>some</td>
<td>yes</td>
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<td>some</td>
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<td>no</td>
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</tr>
<tr>
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<td>yes</td>
<td>no</td>
<td>none/faint</td>
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<td>yes</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td></td>
<td>yes</td>
<td>no</td>
<td>stronger than BL Lac</td>
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<td>yes</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
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<td>some</td>
<td>some</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
</tbody>
</table>
Quasars:

Active Galaxies:
http://csep10.phys.utk.edu/astr162/lect/active/active.html

Galaxy spectra:
http://csep10.phys.utk.edu/astr162/lect/active/AGN_galspecS.swf

Summary
Active galaxies are galaxies that are associated with variability over short time periods, violent events in their nuclei, high luminosity, and non-thermal, or non-blackbody, emission. The Milky Way galaxy is relatively quiet at radio wavelengths. Radio loud galaxies can be divided into two types: core-halo radio galaxies and double-lobed radio galaxies. Many radio galaxies are seen relatively nearby. Core-halo radio galaxies are typically elliptical galaxies with a compact radio-emitting core. Double lobed radio galaxies consist of a pair of enormous and high radio luminosity lobes with an optically visible galaxy typically found almost precisely midway between the lobes. In both cases the radio emission is produced by high velocity electrons spiraling along a magnetic field.

At greater distances we find Seyfert galaxies and BL Lac objects, both superluminous galaxies. Seyfert galaxies are spirals whereas BL Lac objects have an underlying elliptical galaxy. At even greater distances, as far away as 10 billion light years are the most active, most luminous galaxies, quasars. Quasars are seen at the look-back time
corresponding to the initial epoch of galaxy formation in the Universe. They represent the most luminous galaxies that we can see.

The size of the energy source powering a variable galaxy can be estimated from its period of variability. Active galaxies in general and quasars in particular present a problem in modeling such a large source of energy in such a small volume. The central engines of active galaxies are thought to be supermassive black holes with hot accretion disks producing narrow jets of high velocity particles.

**Key Words & Phrases**

1. **active galaxy** – any galaxy which shows abnormally high luminosity, the appearance of past episodes of violent activity, a highly non-thermal emission spectrum, or significant variability of luminosity
2. **BL Lacertae object** – an active elliptical galaxy with a superluminous nucleus and variability on the time scale of a year

3. **Core-halo radio galaxy** – a radio galaxy with intense radio emission from a small core and weak or nonexistent radio emission from the surrounding galaxy

4. **Double-lobed radio galaxy** – a radio galaxy with two enormous radio lobes and a visible galaxy found midway in between

5. **Non-thermal emission** – an emission spectrum that deviates a great deal from a blackbody spectrum or the sum of a series of blackbody spectra

6. **Quasar** – a high-red shift active galaxy with a stellar appearance

7. **Radio galaxy** – a galaxy that emits an unusually large amount of energy in the radio portion of the electromagnetic spectrum

8. **Seyfert galaxy** – an active spiral galaxy with a superluminous nucleus, variability on the time scale of a year, and broad nuclear emission lines indicating high-velocity gas motions
Review for Understanding

1. What are quasars? How does their observed variability make it more difficult to explain their brightness?
2. If only a small percentage of galaxies are observed to be undergoing explosive phenomena in their nuclei, does this mean that the average galaxy, like our own, does not ever undergo this type of event? Why or why not?

Essay Questions

1. Starting with the size of the Earth’s orbit, outline all the steps one has to go through to find the distance to a quasar of known red shift.
2. A typical supernova has $10^9$ times the luminosity of the Sun at maximum brightness. An O-star has a luminosity of about $10^5$ times that of the Sun. Discuss whether or not it is realistic to explain the luminosity of the most luminous quasars as (a) a large number of supernovae at the center of a galaxy, or (b) an intense burst of star formation at the center of a galaxy.