Black Holes in Fact

Exploring the Reality

1. The Search for Black Holes

Black holes, those made from stars, are really black! How can we hope to find them if they do exist? Some solitary massive stars may collapse to make isolated black holes drifting through the emptiness of space. There could be very many of these black holes. Estimates based on the number of massive stars that have died in the history of our Galaxy range from one to a hundred million black holes. The simple fact is that, until a space probe stumbles into one, we are likely never to detect this class of isolated, single black holes. We will certainly never see the black hole itself in any circumstances because no light emerges from it. Our only chance to detect the presence of a black hole is to find a situation where mass is plunging down a black hole, heats, and radiates. We can hope to detect the halo of radiation from such an accreting black hole even if we never see the black hole itself. Black holes are so strange and so significant that the standard of proof must be exceedingly high. As we will see, the evidence is very strong, but still largely circumstantial.

Many astronomers search for giant black holes in the centers of galaxies. The evidence for those black holes has become rather strong in the last few years, but most of the evidence still involves matter moving far beyond the event horizon, and we know very little about the configuration of the accreting matter. There is no question that there are concentrations of gravitating mass in the centers of galaxies, including our own, that contain millions if not billions of solar masses, are small, and are not radiating anything like an equivalent amount of star light. One idea is that they could be a cluster of compact stars, neutron stars, or stellar mass black holes, but the theory of such swarms of objects says they should quickly collide and merge and make one large black hole. With some theoretical underpinning and compelling circumstantial evidence, the argument for these giant black holes is rather convincing. There are clues from the X-rays from some galactic cores that the space near the very center has just the character you would expect for that around a rotating, supermassive, Kerr black hole. More evidence of this kind may remove any ambiguity.

Another excellent hunting ground for black holes has proved to be in binary star systems where mass transfer can feed the accretion and produce X-rays in the high gravity of a stellar-mass black hole. Here also the case has become very strong that we are observing black holes. This facet of black hole research is closely connected to the topics covered in this book, so this story is worth telling in more detail.

Over thirty strong X-ray sources have been established to be in binary systems. Of these systems, about a dozen have some determination of the mass of the X-ray source itself. In most cases, the mass is in the range of one to two times the mass of the Sun. These are probably neutron stars. In some cases, pulsations are observed, and the case for rotating, magnetized neutron stars is clearly established. One should perhaps bear in mind, however, that, although a neutron star cannot have a large mass, there is no reason in principle why a black hole could not have a modest mass, particularly if it formed by adding a bit too much mass to a neutron star. We still have no unambiguous way of determining that we have a black hole with a mass less than the maximum mass of a neutron star, although there are some ideas for how to do this.

In the case of a black hole, there is no question of radiation from the surface of the object because there is no matter, only the ephemeral event horizon. All the X-rays must come from matter in the accretion flow. Within about three times the radius of the event horizon of a black hole, the gravity is so strong that the matter cannot spiral in a disk but must plunge headlong into the hole. In this state, the matter radiates much less because it is not subject to the friction of the accretion disk. In addition, the radiation emitted from this region is highly red-shifted, so it is difficult to detect with X-ray devices. Any X-rays detected from an accreting black hole will come from a halo in the disk, inside which there is only blackness. This particular way in which X-rays are emitted may prove sufficiently different from the X-ray emission mechanisms for neutron stars that black holes can be unambiguously identified, independent of their mass. For now, the story is a bit less certain.

2. Cygnus X-1

One of the first binary X-ray sources discovered is a candidate black hole system. This object was the first X-ray source discovered by the *Uhuru* satellite in the direction of the constellation Cygnus. Soon after its discovery, astronomers were describing Cygnus X-1 as a possible black hole. Absolute proof escapes us, but the net of circumstantial evidence has grown ever tighter. Cygnus X-1 is probably a black hole.

The chain of arguments proceeds like this. The fact that Cygnus X-1 emits a strong flux of energetic X-rays at all argues that it is a compact object with a large gravitational field. It could be a white dwarf, a neutron star, or a black hole. The intensity of the X-rays argues against the white dwarf possibility. Added evidence against a white dwarf is that the X-rays from Cygnus X-1 flicker on a time scale of milliseconds. We can use an argument based on how far light can go in a given time to say that the object must be smaller than the distance light can travel in 0.001 second. That distance is 300 kilometers, consistent with a neutron star or a black hole, but too small to be a white dwarf. A white dwarf would be too large and sluggish to vary rapidly. The conclusion that Cygnus X-1 is not a white dwarf, never mind an ordinary star, seems quite sound.

This leaves us with a neutron star or a black hole as the necessary object. There may be a foolproof way to tell the difference from the nature of the X-ray emission alone, but that argument is still under development and is difficult to apply cleanly to Cygnus X-1. Many feel that the millisecond fluctuations are themselves evidence of the nature of a black hole, but that has not been proven. The lack of regular pulsations is not sufficient because the object could be a slowly rotating or unmagnetized neutron star that could not produce detectable pulses. The only way we know to distinguish between a neutron star and a black hole is to argue that a black hole can exceed two or three solar masses, and, as discussed in Chapter 8, a neutron star cannot.

Careful study of the Cygnus X-1 system, both the X-ray source and its companion massive star, shows that the companion has a mass of about 30 solar masses, and the X-ray source, a mass of about 10 solar masses. The latter is too much to be either a white dwarf or a neutron star. By a process of elimination, the reasonable conclusion seems to be that Cygnus X-1 is a black hole.

The presumption behind this chain of reasoning is that the massive star transfers mass to the black hole, and the infalling matter emits X-rays before it plunges into the black hole, but all we really know for Cygnus X-1 is that a 10 solar mass "thing" is emitting X-rays. As an example, let us consider a way in which nature might be playing a trick on us. We know that triple-star systems are present in the Galaxy. We noted in Chapter 3 that the nearest star, Alpha Centauri, is in a triple system. Suppose that Cygnus X-1 consists of a neutron star of 1 solar mass orbiting an ordinary star of 9 solar masses, and that the pair of them are orbiting another ordinary star of 30 solar masses. If the 9-solar-mass star transfers mass to the neutron star causing the emission of X-rays, then we will have an X-ray source with total mass of 10 solar masses orbiting a 30-solar-mass star, just as the observations demand, yet there would be no black hole. This picture is unlikely, but not entirely impossible. The reason we can consider it at all is that the 30-solar-mass star would be considerably brighter than the 9-solar-mass star, so the latter could be lost in the glare. Attempts have been made to detect such a masquerading companion by searching for faint spectral lines that would shift around among the spectral lines of the brighter star as the Doppler shift responds to the orbital motion. No hint of such a secondary star has been forthcoming. It probably is not there, but a tiny doubt will always linger.

The massive companion to the X-ray source in Cygnus X-1 is blowing a stellar wind, as such stars do. The picture adopted for Cygnus X-1 is that the gravity of the black hole traps part of the wind. That matter then swirls into an accretion disk. The matter then spirals down, and the friction heats the gas to temperatures where the matter radiates X-rays. The companion is transferring mass at a sufficiently slow rate that it seems unlikely that the black hole in Cygnus X-1 could have started as a neutron star and then collapsed to a black hole and subsequently grown to its present mass before the companion died. The presumption is that the black hole formed directly by the collapse of a 10-solar-mass object.

It does not follow that the black hole arose from a star whose initial mass was only 10 solar masses. A more likely prospect is that the progenitor star had a mass of around 35 solar masses. The other star, the normal companion that still exists, probably had about the same mass we see now, around 30 solar masses. Stars of 30–35 solar masses develop helium cores of about one-third their original mass. The originally more massive star thus probably grew a helium core of about 10 solar masses as it burned up the hydrogen in its center. At the same time, the star probably lost a great deal of mass due to its own stellar wind. The most likely time for this is when the originally more massive star finally exhausted its central reserve of hydrogen and began to become a red giant. At this time, any mass remaining above the helium core probably flowed out of the binary system or onto the companion star. During this episode, the companion could have lost some mass to a wind and gained some from the more massive star, so it did not change appreciably.

Even though it has lost its hydrogen blanket, the now bare 10-solar-mass core of the first star is so massive that it is supported by the thermal pressure and continues to evolve with regulated nuclear burning. The core presumably burns a series of nuclear fuels until it forms an iron core. This core collapses, but instead of producing the explosion of a supernova, a black hole forms. All the matter in the core rains down through the event horizon. The net effect is that the 10-solar-mass black hole did not come from a 10-solar-mass star but more likely from one originally with somewhat more than 30 solar masses. The corollary implication is that this star did not explode but left a black hole instead. One is invited to think that all stars in this mass range, greater than 30 solar masses, leave black holes. A possible problem with this reasoning is that the very fact that the star was in close orbit with a massive companion may have altered the evolution in a way we do not understand. As we discussed in Chapter 6, there is little direct evidence concerning the end point of massive stars of a given initial mass. In any case, a common presumption is that stars of about 30 solar masses must explode to provide the heavy elements. Clues that stars of this mass make black holes means that there is no strong evidence to support this presumption.

3. Other Suspects

Further observations showed that there are binary systems emitting X-rays that provide even better evidence for black holes than the famous Cygnus X-1.

One of these systems is LMC X-3. This object is the third X-ray source discovered in the nearby galaxy, the Large Magellanic Cloud, which also played host to Supernova 1987A. LMC X-3 is similar to Cygnus X-1 in that the X-ray source seems, from a study of orbital parameters, to have a mass of about 10 solar masses, and hence to be too massive to be a neutron star. In this case, however, the companion star is only about 10 solar masses as well. This means that it is much more difficult to hide a third star in the glare of the ordinary star than in the case of the more massive, and brighter, companion in the Cygnus X-1 system. A three-body system with a neutron star orbiting an undetected normal star, with both orbiting the observed normal star, would be untenable. There would be obvious evidence of the third star. LMC X-3 may thus be a better candidate for a black hole than Cygnus X-1 because one cannot resort to the dodge of hiding some other source of mass and gravity in the system.

There is, however, a system in our Galaxy that is an even better candidate for containing a black hole in orbit. That is the system with the boring moniker AO620-00, named for its directional location in the Galaxy. This system seems to have a 5-solar-mass black hole orbiting a normal star that is not massive at all but about one-half the mass of the Sun. It is not clear how a star with original mass of about 30 solar masses, that could have a core of about 10 solar masses, which in turn could collapse to make a black hole, would come to have such a wimpy companion. Usually massive stars seem to hang out with one another. On the other hand, nature may be tricking us here. If every 30-solar-mass star had a 0.5 solar-mass companion, the dinky star would be lost in the glare, and we would never know it. Nature may form stars in this way much more frequently than we realize, or there may be something else going on that is special to black hole systems. One suggestion is that the little companion star forms from the matter spun off the star that forms the black hole. In any case, the small-mass, dim companion means that it is virtually impossible to hide another star in the system to trick us into thinking that an X-ray-emitting neutron star had a higher mass, therefore masquerading as a black hole.

Another argument adds to the case. AO620-00 underwent at least two outbursts that produced an excess light output, one in 1917 and one in 1975. The 1975 eruption produced a corresponding detected burst in X-rays. These bursts lasted for about a month and, in the optical at least, are rather reminiscent of dwarf nova outbursts. Models of the behavior of accretion disks around black holes reproduce the properties of the optical and X-ray bursts with the same kind of physics that works for dwarf novae, as discussed in Chapters 4 and 5. The accretion disk collects matter until it undergoes an instability that dumps matter into the black hole at a greater rate, resulting in the outburst.

The arguments are still circumstantial. What we know is that AO620-00 contains an orbiting object with a large mass that emits X-rays but virtually no optical light. Nevertheless, it is very difficult to see how AO620-00 could be anything but a black hole.

There is a bit of a tendency to cry "black hole" whenever a strange new astrophysical phenomenon involving high energies turns up. That is one reason most astronomers are trying to be as conservative as possible about concluding that Cygnus X-1, LMC X-3, and AO620-00 are black holes. There is another danger: there are other black holes out there, and we are being too conservative to face the facts. The last few years have revealed that the Galaxy is full of systems like AO620-00.

4. Black Hole X-Ray Novae

One way to beef up our confidence that Cygnus X-1, LMC X-3, and AO620-00 are black holes is to find others. There is safety in numbers. The problem is that the combination is rare wherein a massive star makes a black hole, and we catch a comparably massive companion as it is transferring mass, but before the companion also dies. Only about one such pair should exist in the Galaxy at any one time. We may have discovered that one rare event in Cygnus X-1. It is possible that LMC X-3 is the only currently active black hole with a massive companion in that smaller galaxy, just as Cygnus X-1 may have that single merit in our Galaxy. The formation of black holes is associated with massive stars, and Cygnus X-1, the grand-daddy of black hole candidates, has a massive companion. The feeling lingered for a long time that all black hole binaries, if they existed, would resemble Cygnus X-1. In the last decade or so, we have learned that the Galaxy is full of binary black hole candidates, but, like AO620-00, they are wonderfully and surprisingly different from Cygnus X-1. These systems are even better candidates for black holes than the venerable Cygnus X-1, and they present better laboratories to explore the astrophysics of black holes.

Two basic characteristics distinguish the new class of black hole candidates, of which AO620-00 is the prototype. They show a distinct transient behavior, and they have low-mass, relatively dim companions. These systems maintain a quiescent state for decades and then erupt in a sudden burst of energy. The energy output appears throughout the range of electromagnetic waves from radio to gamma rays. There is especially interesting behavior in the soft and hard X-ray bands. The outbursts last for about a year, and then the system fades to quiescence again. In the quiescent state, the only evidence of the system is the small-mass companion. Without an eruption to draw the attention of astronomers, these stars are lost among the billions of similar stars in the Galaxy. Without the ability to detect the associated high-energy emission in X-rays and gamma rays, even the outburst may pass without special notice. Such eruptions may have been mistaken for classical novae in the past.

When AO620-00 underwent an outburst in 1917, before the invention of X-ray astronomy, it was taken for an ordinary nova. AO620-00 had a dramatic X-ray outburst in 1975, but it was several years later before evidence came in that it might harbor a black hole. Only relatively recently has the realization dawned that the Galaxy contains many of these systems. The coverage of the sky with satellites that can monitor X-ray outbursts has been fairly thorough for the last decade. The result is that astronomers have discovered X-ray novae that are black hole candidates at the rate of about one per year in the Galaxy for the last 10 years. Because these systems sit quietly undetected for perhaps 50 years for every year they are in outburst, then every one outburst may represent 50 sleeping systems. Our vigilance in watching the Galaxy is not perfect, and gas and dust could obscure some events. Allowing for such problems, one can guess that there could be 100 to 1,000 such black hole systems in the Galaxy. Thus they vastly outnumber systems like Cygnus X-1.

One of the principal goals in the study of these erupting systems is to find proof that they contain black holes, not neutron stars or some other configuration that can mimic the circumstantial evidence for a black hole. Currently the most reliable way to establish a black hole candidate is to show that the compact object in a binary system has too much mass to be a neutron star.

Five or six black hole novae are excellent black hole candidates. These systems have at least a firm lower limit to the mass of the object emitting the X-rays that rules out a neutron star. Among these are AO620-00, V404 Cygni and Nova Muscae 1991. V404 Cygni is currently the best candidate for a black hole in a binary system. Many careful observations reveal that the mass of the compact star is about 12 solar masses, far more than is possible for a neutron star. Approximately another two dozen systems are good black hole candidates based on the similarity of their optical and X-ray outburst behavior to the temporal and spectral behavior of the best established candidates.

In most of the black hole X-ray novae, the companion has a small mass. The companion stars are dim and hence difficult or impossible to detect even when the system is at minimum light. In the systems where information is available about the mass of the compact object, there is also information about the mass of the companion. In AO620–00 and Nova Muscae 1991, the normal star companion is substantially less than 1 solar mass. V404 Cygni is somewhat a special case. The companion has evolved past the main sequence stage, but even then the remainder of the star has a mass of only about 4 solar masses. For most of the systems, the companions are low-mass, low-luminosity stars, with a mass considerably less than the mass of the putative black hole. There is no question of a third star masquerading in any of these systems, adding mass that would be mistakenly attributed to the compact object.

5. The Nature of the Outburst

To obtain a basic understanding of the behavior of these systems one of the most important questions to address is the reason for the outburst. The most promising model for the basic outburst is an instability not directly associated with either the black hole or the companion star, but within the accretion disk that passes matter between them. The companion star provides the reservoir of mass. If the mass flows too slowly from the companion, the accretion disk cannot remain in a hot, ionized state, and a steady rate of flow is not possible. These systems must undergo accretion disk outbursts similar to those in dwarf novae and some neutron star binary systems, as discussed in Chapters 5 and 8. In the simplest picture, the disk flares to make excess optical and X-ray radiation and then goes back into storage mode, accepting matter from the companion, but passing very little through itself and down the black hole. The disk emits little optical light and virtually no X-rays. The main thing observable in this state would be the companion star and perhaps the spot on the edge of the disk where matter rains in from the companion. The disk could develop a very hot, nearly spherical inner region, as discussed in Chapter 4 (Figure 4.6), which would alter this simple picture and give another source of luminosity in the "off" state. We will return to this topic in the next section.

This physical process of the disk instability does not depend on the exact nature of the compact object or of the star providing the mass. It can happen to accretion disks surrounding white dwarfs and neutron stars as well as black holes. The majority of the X-ray novae that display this outburst behavior show no explicit evidence for neutron stars and remain black hole candidates.

The disk outburst model can account for the decade-long periods of quiescence, which are set by the time for matter to collect or ooze inward in the cold, low-viscosity disk. The rapid rise time of days can be associated with the time scale for heating waves to propagate in the inner disk. The year-long decline is governed by the more rapid viscous evolution in the hot state and the time for the cooling wave to propagate through the disk.

There are some explicit tests of this picture. The model predicts that in quiescence, the mass transfer rate as determined from the luminosity of the "hot spot" where the accretion stream collides with the disk should be far greater than the flow into the black hole as determined from the X-ray luminosity produced in the inner disk. These basic predictions are borne out by optical and ultraviolet observations of AO620–00 from the *Hubble Space Telescope* and X-ray observations with the German *ROSAT* satellite. Other confirming evidence comes from the lack of helium emission lines. If the inner regions generated X-rays, the X-rays would excite the gas to produce fluorescent emission lines. The lack of those spectral features means that there cannot be many X-rays and hence little mass flow in the inner disk. These observations seem to show that the disk is storing matter.

One objection to the model is that the disk does not seem to cool in the decline phase as much as predicted. This may be due to the formation of a hot "corona" around the disk, much like the corona that surrounds the Sun. In that case, the observed surface temperature does not reflect the temperature of the body of the disk that the models predict. Another possibility is that the X-ray flux from the inner disk is not low because the mass flow rate is low, but because the efficiency of emitting X-rays is low. We will discuss this in the next section.

6. Lessons from the X-Rays

Near the maximum of the outburst, lower energy X-rays from the black hole novae show a component that seems to come from a hot, opaque, geometrically thin disk, as predicted by the disk instability models. The observations show no significant change in the inner radius of the disk as the systems cool after outburst. The only characteristic radius in the disk that could plausibly remain constant as the mass flux declines is the last stable circular orbit, within which matter must plummet straight into the black hole. Evidently, near the peak of the outburst, the accretion disk extends all the way down to the inner radius from which matter plunges directly down to the event horizon of the black hole and disappears. This conclusion strongly affects considerations of the higher-energy X-rays that may contain direct clues of the existence and nature of the black hole, rather than the accretion disk.

The black hole novae also show high-energy X-rays, ranging all the way up to gamma rays. A process known as *Compton scattering* can produce these high-energy X-rays when low energy photons scatter from a hot plasma and pick up energy. Arthur Holly Compton won the Nobel Prize in 1927 for his discovery of this effect and was further honored by the naming of the *Compton Gamma-Ray Observatory* (see Chapter 11, Section 2). Neutron star systems rarely display this kind of radiation, and then only in a truncated form. This high-energy radiation may be just the clue we need to clearly distinguish accreting black holes from accreting neutron stars without the need to invoke the mass limit of neutron stars. Some recent theories for this high-energy radiation have made the explicit argument that it can only exist as it is observed from systems with no hard surface. That argument, if confirmed, would rule out not only neutron stars but also some other bizarre suggestions that would nevertheless have a hard surface. The only small-radius, high-gravity objects we can now imagine that do not have hard surfaces are black holes.

This high-energy radiation is seen near the peak of the outburst of many of the black hole X-ray novae. It probably comes from a hot corona surrounding the disk, although the exact nature of that corona remains elusive. The black hole X-ray novae also commonly show radio outbursts that require an outflow of matter with very high energy electrons. This outflow could also be a source of high-energy radiation. The observed interplay between the high-energy radiation from a corona and the lower-energy X-ray radiation that is presumed to come from the accretion disk is complex and varies in time, but as the outburst decays, the high-energy radiation comes to dominate. This suggests a change in the structure of the accretion flow.

One possibility under active investigation is that, as the mass flow rate declines due to the inward propagation of the cooling wave in the disk, the inner disk thins out and reaches a state where it cannot cool efficiently. Rather than dropping into the cold state of an accretion disk, this inner region can become very hot, and nearly spherical. Matter from this dilute, nearly spherical region then falls almost radially straight down the black hole. The basic notion of this sort of flow was outlined in Chapter 4 and is illustrated in Figure 10.1. This material does not radiate much despite its high temperature both because dilute gas does not radiate efficiently and because this matter tends to plunge directly down the black hole, carrying its heat energy with it. In these circumstances, there is little time to radiate. This process is called *advective accretion flow*, to distinguish it from disk accretion flow. In a disk, most of the heat energy is radiated out through the face of the disk. In an advective flow, the heat is carried, or advected, down through the event horizon, so little heat is lost to radiation.

What little heat does radiate from an advective flow should, according to theoretical models, emerge as very high energy radiation, as observed. Because the radiation efficiency is low, a much higher mass flow rate must be sustained in order to produce even the feeble radiation that is seen. When applied to the black hole X-ray novae, this theory suggests that a substantial amount of the mass transferred from the companion star does pass through the disk and down the black hole even when the system is in its long-lived, low-luminosity state. Models based on this picture are rather successful in accounting for the feeble X-rays from the low-luminosity systems, even though the simple disk models say the disk should be cool and in a storage phase. This theory is on the cutting edge of research as this book is being written and so there are a number of questions that have not been completely resolved. Among these are: how a cold disk can pass all the mass it must in order to feed the advective flow; how the advective region forms, perhaps by evaporation of disk matter; whether a substantial amount of matter transferred from the companion is blown away in a wind or other outflow before it can reach the black hole. All these issues are a sign of a vibrant and exciting research area.

One general notion has emerged. If the accreting object had a hard surface, photons from that surface would probably interfere with the matter in the advective region and prevent it from having the properties observed for the black hole sources. This is one version of the argument that the black hole X-ray novae cannot be neutron stars but must be objects with no surface. If this argument is right, they must be black holes, independent of the mass we measure for them.

7. SS 433

Another interesting class of objects in the astronomical zoo consisted for a very long time of a single entry. In 1980, Walter Cronkite brought this discovery to the attention of the world when he announced on CBS News that astronomers had found an object that was coming and going simultaneously! For those of you confused by that, read on.

The object was originally identified as being notable for its *emission lines*, excess power coming out at certain wavelengths of light. Normal stars show absorption by cool atoms, and emission is a sign of an energetic environment in some fashion. The object at issue is source number 433 in the catalog of objects with strong emission lines compiled by two astronomers, Sanderson and Sanduleak, so it is known as SS 433 (this is the same Sanduleak who cataloged the star destined to erupt as SN 1987A). Closer study showed that the emission lines in this object displayed a most peculiar behavior. There are two sets of emission lines, and they move around in frequency in opposite directions because of the Doppler effect. Each set of lines shows first a red shift and then a blue shift. The period of oscillation is 64 days. When one set of lines shows a red shift, the other set shows a blue shift, and vice versa. Thus when the gas causing one set of emission lines is moving toward us, the gas causing the other set is moving away from us, hence Cronkite's comment on the news. The actual interpretation that astronomers have given to this information is that SS 433 is emitting jets of material in opposite directions, but somehow twisting around to throw the beams first in one direction, then in the other. Radio observations show an arcing series of blobs extending out beyond the object. Imagine that you are pointing a water hose overhead, but moving the nozzle in a circle. If you were to take a photograph at one instant, you would see blobs of water strung out along a widening helical path. That is what the radio astronomers see, confirming the picture of the oppositely directed rotating jets.

The real excitement came with the deduction of the velocity of the jet material. The jets are not directed at the Earth, but sideways, so normally one would not expect a Doppler shift. According to Einstein's special theory of relativity, however, even an object moving sideways shows a tiny Doppler effect. With ordinary velocities, the effect is undetectable. In order for there to be a measurable “transverse” Doppler effect in SS 433, the material in the twin beams must be moving at 80 percent the speed of light! SS 433 is ejecting opposing beams of material at nearly the speed of light. Active galaxies and quasars had shown similar jets, but this was the first time a star displayed such phenomena.

A further remarkable feature is that the material in the beams is not hot. SS 433 shows emission lines of neutral helium, but none from ionized helium so the matter cannot be tremendously hot. How the matter accelerates to the speed of light without getting heated in the process is a question that still plagues the theorists. One possibility is that radiation pressure can slowly accelerate the material and never push on it so hard that it gets hot.

SS 433 is surrounded by a radio source identified by the *synchrotron radiation* that arises when electrons spiral around in magnetic fields at nearly the speed of light. Some have identified this radio source as a supernova remnant left from the formation of SS 433. Others point out that if this is so, it is the largest supernova remnant in the Galaxy. A plausible alternative is that the remnant is a bubble blown in the interstellar gas by the relativistic particles ejected in the twin beams of SS 433 itself.

The actual nature of SS 433 still eludes satisfactory explanation. Clearly, the tremendous velocities require high energy and thus probably the high gravity of a compact star. One idea is that SS 433 contains a neutron star that is trying powerfully to emit radiation, perhaps because it is a young and energetic radio pulsar. If mass transfer has totally enshrouded it in a blanket of gas, a common envelope, however, the radio waves could not get out directly. The energy then blasts out of two holes in the top and bottom of the envelope and makes the beams. This notion is given some support by other Doppler shift measurements that indicate that besides the rotation of the beams, the whole object moves about with a period of 13.6 days. This probably represents a binary orbital period. The binary companion is presumably the source of the enshrouding envelope. Other theories attribute the energy to matter being swallowed by a black hole.

SS 433 remains an enigma in many regards, and the search for another object like it anywhere in the Universe went on for over a decade. Its close cousins, if not twins, were discovered only a few years ago.

8. Miniquasars

The black hole X-ray novae discussed in Sections 4 and 5 drew a lot of attention as evidence grew that they were black holes. The specifics were different in detail, but these objects had an inflow of matter, accretion disks, and, very probably, black holes. The same general description applies to the models for the energy sources of quasars and active galactic nuclei. The main difference is that the black holes in quasars are thought to be supermassive, up to a billion solar masses, and those in the black hole X-ray novae were 5–10 solar masses. The latter were clearly formed by the collapse of stars (although the details elude us). We do not know the origin of the supermassive variety.

One aspect of the supermassive black holes in galaxies is that they often emit beams of matter at nearly the speed of light. SS 433 was a hint in the direction that stellar mass black holes could do the same thing, but ambiguity about its nature prevented a direct analogy from being drawn. That situation changed dramatically in the mid-1990s with the radio study of the outbursts of some of the black hole X-ray novae.

Felix Mirabel is a radio astronomer of Argentine extraction who works in Paris. Luis Rodriguez is a Mexican radio astronomer. They began a project to monitor the radio emission of the black hole X-ray novae. In 1994, they got data on an outburst in an otherwise obscure source that is hidden behind so much galactic dust that it cannot be seen with optical telescopes. The radio emission can penetrate the dust. Mirabel and Rodriguez discovered a remarkable behavior. They could identify discrete clouds of particles ejected from the X-ray source that emitted radio radiation as they moved rapidly away from the central source. By watching these clouds from day to day, they could see how far apart they had moved in a given time interval. A simple calculation of their speed showed that they seemed to be moving at greater than the speed of light!

This apparently superluminal behavior had been seen before. It was first noticed 30 years ago when similar monitoring was done of quasars. This does not represent a breakdown of Einstein's theory, but a sort of relativistic optical illusion. The explanation for this phenomenon gave Sir Martin Rees, the eminent British astrophysicist, his first claim to scientific fame. The answer to this puzzling behavior is that the matter is ejected from the central source at nearly, but not quite, the speed of light. For the sources that appear superluminal, the jets of matter are pointed nearly toward us. In this case, the matter is chasing the radiation it emits and traveling at nearly the same speed. This foreshortens the apparent motion of a blob of emitting matter in such a way that it seems to be covering a large angle, and hence a large reach of space, in an impossibly short amount of time. The X-ray nova that Mirabel and Rodriguez observed was doing the same thing. The matter was being ejected in blobs that moved at nearly, but not more than, the speed of light, thus giving the appearance of superluminal motion.

At least one other black hole X-ray nova has been discovered to display this superluminal motion. The second one has a measured mass for the compact object from the binary orbit that it is more than 3 solar masses. This puts it firmly in the category of black hole candidate. The miniquasars have helped to put SS 433 in context. There are differences, but there are also obvious similarities. Even though there is still no firm proof that SS 433 is a black hole, we can deduce that if the jets of SS 433 were pointed more nearly directly at us, we would witness nearly, if not clearly, apparent superluminal motion.

The analogy between the black hole X-ray novae and quasars as supermassive accreting black holes was already quite strong, but the discovery of the X-ray novae with apparent superluminal motion cemented the idea in many people's minds. The phrase “mini-quasars” instantly became popular to describe the black hole X-ray transients, especially those with the superluminal behavior. There is much to be learned about how black holes of either the stellar or supermassive variety launch the rapidly moving blobs of radio-emitting matter, but the discovery of the miniquasars is one more piece of evidence that black holes really exist on both the stellar and supermassive scales.

9. Giants Among Us

The study of quasars has convinced astronomers that the only credible explanation for the immense luminosity, small size as indicated by the daily variability, and immense, sometimes superluminal, jets, is that they are powered by supermassive black holes. As described in Chapter 2, Section 2, accreting objects cannot have a luminosity brighter than the Eddington Limit luminosity, or they would blow the surrounding matter away with radiation pressure rather than accreting it, the very mechanism needed to produce the luminosity in the first place. The Eddington limit in turns depends on the mass of the accreting object; a larger mass with higher gravity can withstand a brighter, self-induced radiation, and still manage to draw matter inward. Accreting objects must then have a mass big enough that the Eddington Limit to the possible luminosity is comfortably above the luminosity actually observed. This means the mass of the object must be big enough to withstand the observed luminosity. Estimates based on the Eddington luminosity argument as applied to the incredibly bright quasars yield estimates for the mass that range up to a billion solar masses for the very brightest.

Ironically, it has proven rather difficult to absolutely establish that quasars harbor these giant black holes. Velocities of gas believed to orbit near the black hole are consistent with the suspected large masses. In addition, recent observations with the Chandra X-ray Observatory and the XMM-Newton X-ray Observatory have revealed information from near the center that strongly suggests not just a black hole, but a Kerr black hole with rather specific rotational properties in some active galaxies. The assumption that quasars represent supermassive black holes is certainly consistent with all we know of quasars and more specific data is promised. In the meantime, other evidence that such large black holes exist in the centers of galaxies has come from the study of more normal galaxies, such as our own Milky Way.

Investigations of giant black holes in ordinary galaxies were driven in part by the desire to understand what becomes of a quasar when it is no longer a quasar. In the standard picture, material from the surrounding galaxy must rain down on the central black hole so the luminosity can arise from the accreted mass, most likely from a large accretion disk. If that mass flow shuts off, the quasar activity will die out, but any black hole will still be there. Quasars are observed at large distances and from back in the past. The question is how many current, quiet, galaxies were once quasars and whether or not we can find evidence for their black holes.

Perhaps the most dramatic success in this field is the discovery and study of the supermassive black hole in the center of our own Milky Way Galaxy. The center of our Galaxy, in the direction of the constellation Sagittarius, is shrouded by the lanes of gas and dust in the disk of the Galaxy through which astronomers must peer to see the center. Ordinary optical astronomy is useless. Rather, astronomers have used longer wavelength radiation, infrared and radio to penetrate the murk. The target has long been a bright radio source known as Sagittarius A. The gas swirls around this region in a way suspiciously like gas falling into and swirling around a central source of gravity. A practical worry is that gas is subject to ephemeral forces of other sorts, other gas streams, the pressure of radiation, the guiding hand of magnetic lines of force. This gives caution about a literal interpretation of the swirling gas as caused only by a massive source of gravity, and yet that may prove the correct and simple interpretation. The most dramatic insights have come from studying the motions of stars near the Galactic center. Stars are like tough little nuggets. Their orbits are not swayed by streams of interstellar gas, magnetized or otherwise. They proceed like a bullet through a sandstorm, orbiting through the local gravitational field (the curved space!) caused by the collection of other stars and any giant single mass that might be present.

Unlike optical radiation, longer wavelength, infrared and radio radiation can penetrate the murk between us and the center of the Galaxy. By observing the infrared radiation of stars, two teams of astronomers, one led by Reinhardt Genzel at the Max-Planck-Institut für Extraterrestriche Physik in Munich and one by Andrea Ghez at UCLA have tracked the motions of individual stars near the center of the Galaxy, in a region smaller than the size of the orbit of Pluto, about 20 light days across. This technical tour-de-force has revealed not simply higher velocities of stars near the center, but with observations spanning a decade has shown the orbits of individual stars as they plunge, accelerating, toward the central source of gravity and then recede to outer, slower portions of the individual orbits. The result is unambiguous: there is a tiny, very dark, four-million solar mass concentration of gravity right at the dead center of our Galaxy. If this concentration of mass were a swarm of other dark objects, neutron stars or stellar mass black holes, they would quickly coalesce into a supermassive black hole anyway! The conclusion seems inescapable that our Galaxy contains a four-million solar mass black hole. Astronomers are not resting on their laurels. What is needed next is an actual "photograph" of the dark spot, or other evidence of the strong Einsteinian curved space very near the event horizon. Such an observation may be possible in the near future with radio telescopes and aggressive plans are afoot to do so.

In the meantime, other teams of astronomers have sought evidence for supermassive black holes in other galaxies scattered about the nearby Universe. My colleagues here at the University of Texas, John Kormendy and Karl Gebhardt, have been among the most ambitious and successful "black hole hunters." The search for supermassive black holes in normal galaxies proceeds not by looking for a large black dot, but by looking for evidence that stars orbiting near the center of the galaxy are caused to move more rapidly in the gravity of the black hole. This effort requires peeking with great sensitivity right in the heart of galaxies to see, on average, how fast the stars there move. One cannot see individual stars in these more distant galaxies, but the collective motion of the stars will broaden the spectral lines of light emitted by the stars. The average motion can be measured by the average Doppler shift. The Hubble Space Telescope with its great visual acuity played a key role in providing the needed data. The answer is that nearly all decent-size galaxies harbor black holes and that many, if not most, galaxies could have been quasars in the past.

This work has provided an amazing new insight into the nature and import of these supermassive black holes, with Karl Gebhardt again playing a leading role. Decades ago (when my Texas colleague Greg Shields and I worked on this topic), it was thought that supermassive black holes were somewhat incidental to the host galaxy. The implicit assumption was that the black holes formed from matter that was left over from the formation of stars or shed by stars as they involved and that drained toward the center of the galaxy, by uncertain processes. The size of the black hole could then be large or small, depending on the circumstances, but the assumption was that its presence was otherwise incidental to the galaxy as a whole. Instead, the new observations revealed that essentially every galaxy with a central bulge of stars, as possessed by our Milky Way and the nearby giant spiral galaxy Andromeda, contained a supermassive black hole. More dramatically, the mass of the black hole tracked in exact proportion to the mass of the bulge. Every bulge was about 800 times more massive than the central black hole. Galaxies that made more massive bulges made more massive central black holes, or vice versa. To understand how remarkable this statement is, it is useful to note that the mass of the bulge is determined by measuring the average velocities of the stars that comprise it. This means that the velocities of the stars in the bulge are closely connected to the mass of the central black hole even though the stars in the bulge are vastly too far away from the central black hole to feel its gravity now. Yet somehow these distant stars "know" about the presence of the black hole. How can this be?

The answer to this new profound question is not yet known. An idea that is gaining currency is that when the black hole first forms, the radiation from the accretion activity blows a strong wind that limits the mass that gather in the black hole. Perhaps magnetic fields play a role in the feedback process. The general implications are clear. Somehow the mass of the central black hole is intimately connected to the basic processes of the formation and evolution of the galaxy as a whole. This revelation has spurred a great deal of theoretical activity and provided an even deeper rationale to search for black holes.

Another related area that is a current focus is the quest to find quasars at the greatest distances and hence in their most extreme youth. The youngest quasars found arise when the Universe was very young, only about 700 million years old. These quasars are seen shortly after the gas in the Universe was re-ionized after its cold hiatus in the Dark Ages that followed the Big Bang (Chapter 11, Section 1.6). Before that the opacity of the gas was so high that it would be difficult to see things even as bright as quasars. Quasars probably do exist within the early murk. The problem is that astronomers are not at all sure how supermassive black holes could have grown so quickly. Mass can be thrown down their maws only as fast as the generated radiation pressure allows. If mass begins to flow in too quickly, so that the Eddington Limit luminosity (Chapter 2, Section 2) is exceeded, then the matter is instead blown away. This feedback limits how fast a black hole could grow by accretion alone. It may be that the first seed black holes formed from the collapse of massive stars were already pretty large, hundreds of solar masses, giving them a leg up. My colleague Volker Bromm argues that the first stars to form after the Dark Ages were massive, so this might fit together. Such black holes might settle into one another's gravity wells, spiral together by gravitational radiation and merge. Such a growth process would side-step the Eddington limit and might be a very effective way to create supermassive black holes very quickly.

10. The Middle Ground

Yet another hunting ground for black holes has arisen in an unexpected quarter. As noted in the previous section, the luminosity of an accreting object can help to guide an estimate of the mass. If the luminosity is greater than the Eddington Limit (Chapter 2, Section 2), mass would be blown away by the radiation pressure from the star rather than accreting on it to provide the very luminosity observed.

With this understanding as background, X-ray astronomers have found sources of X-rays in nearby galaxies that are very bright; brighter than the gravity of a mere neutron star could hold together. These have been named Ultra Luminous X-ray Sources or ULX. At face value, the observed luminosity requires not only more mass than a neutron star can support, but more mass than binary black hole candidate systems that are produced, as we suspect, from "normal" massive stars. In order to have the Eddington limit luminosity meet or exceed the observed X-ray luminosity, the accreting object apparently must have more than 100 solar masses. To explain this new category of X-ray sources, astronomers began talking about "intermediate mass black holes," black holes with considerably more mass than that suspected in Cygnus X-1 or those in black hole X-ray novae like A0-620-00 or V 404 Cygni, but far smaller than the million to billion solar mass monsters that reside in the centers of galaxies. The ULX remain a topic of hot debate. Just as for quasars in the early days, it is difficult to prove that the source is a black hole. One has to rule out the possibility that the source is a cluster of smaller mass objects that somehow mimic a single large mass. People are scrutinizing the spectrum of the X-rays to see if there are differences from "normal" binary X-ray sources that could be a clue to the nature of the gravitating object.

Suspicion that intermediate mass black holes could exist, and account for the ULX, has been fed from another quarter, the search for black holes in the center of star clusters. The target has been the beautiful globular clusters, nearly spherical clusters of hundreds of thousands of small mass stars that occupy the halo of the Milky Way and other galaxies. Globular clusters are thought to date from the epoch of formation of the galaxies themselves. Once again the means to search for black holes in the centers of these clusters is similar to that for the search for supermassive black holes in the centers of galaxies; look for the motions of stars that belie a large dark mass in the center. Karl Gebhardt has again been a key player in this quest. Such studies have revealed that at least a couple of globular clusters might have concentrations of dark gravitating mass in their centers. The cluster M15 in the Milky Way may have a central dark mass of 4000 solar masses. The cluster called G1 in our sister spiral, the Andromeda galaxy, may have a central dark mass of 20,000 solar masses. If either or both of these lines of evidence in globular clusters pans out, then yet another venue for black holes may have been discovered.

While the direct evidence for black holes in terms of a “dark spot” yet eludes us, there is a particular clue suggesting that these central knots of gravity in globular clusters may be black holes. The mass of the black hole candidates seems to be the same ratio to the globular cluster mass as does the galactic bulge mass to supermassive black hole mass; the candidate black holes have a mass about one thousandth that of the globular cluster mass. Both galactic bulges and globular clusters are old. Both galactic bulges and globular clusters are roundish. Both galactic bulges and globular clusters appear to contain black holes that are a regulated fraction of the total mass. The physics that controls the formation of bulges and supermassive black holes may, then, apply all the way down in scale to the mass of globular clusters and their black holes. If this remarkable concordance proves true, then there is a hint that there is some powerful controlling physics at work.

Are the ULX black hole candidates related to the globular cluster candidates? Globular cluster sources are not necessarily bright in X-rays nor are any ULX in globular clusters. The globular clusters require larger black holes than would the ULX, but there might be some continuum from stellar mass black holes, to ULX black holes, to globular cluster black holes and then on up to the largest found in the brightest quasars. The black holes in globular clusters might not be presently accreting a lot of matter and there might be intermediate mass black holes in environments other than globular clusters. Astronomers have noted that starting with such large black holes might help to grow the supermassive variety more quickly through accretion or by merging them together to jump start the process in a way that would make the Eddington limit luminosity irrelevant to the rapid growth. Certainly there is much more to learn about whether or not intermediate mass black holes exist and, if so, their role in Nature.