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Black holes in stars and galaxies

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For 200 years, black holes have been a solution looking for a problem. In the last two decades they have moved to become a real scientific phenomenon. Black holes exist both as stars in our own Galaxy (identifiable as members of binary stars that emit X-rays) and as the centres of energetic galaxies (‘active galactic nuclei’). The last decade has seen the first accurate mass measurements of these black holes, which lie in the range from five times the mass of our own Sun to many million times. We also have clear evidence for the way that black holes accrete material as their primary energy source. Furthermore, the presence of super-massive black holes has been established in some nearby galaxies, and in the centre of our own Galaxy, from their gravitational effect on nearby stars. Some observations show processes that occur very close to the black hole, where the field of gravity is strong enough to test General Relativity. Recent observations suggest the existence of intermediate mass black holes of an as yet unknown origin.

Introduction

John Michell was a cleric, astronomer and professor of geology at Cambridge. In a speculative lecture to the Royal Society in 1783 he developed ideas about the effect of gravity on the light from the Sun. He based his ideas on the theory that sunlight was corpuscular – small particles, which radiate from the Sun towards Earth. He knew that it was well established from observations of the timing of eclipses of Jupiter’s satellites by Ole Römer in the 17th century that light particles had a finite speed, now measured as 300 000 km s^{-1}. He assumed that when the corpuscles were emitted from the Sun, they were emitted at that speed but slowed down as they radiated from its surface, due to the effect of gravity as laid down by Isaac Newton. The Sun is of such a size and such a mass that the effect of this ‘slow-down’ is small. But Michell calculated that if the Sun were 500 times larger by radius and of the same density, so that its mass was 100 million times its actual mass, then the corpuscles would slow to a halt and not escape from the Sun at

Table 1. The size of black holes

Object	Mass	Schwarzschild radius
A galaxy	1 thousand million Suns	10 AU*
A cluster of stars	1 million Suns	The solar diameter
A large star	100 Suns	150 km
An average star	1 Sun	1.5 km
A planet	1 Earth	4 mm

* 1 AU, or Astronomical Unit, is Earth–Sun distance

all. In this lecture, Michell grasped the essentials of the theory of black holes, the first appearance of the concept in science. Pierre-Simon Laplace put forward a similar concept in 1795.

The modern theory of black holes is expressed, not in terms of gravity as the force imagined by Newton, but in terms of General Relativity as imagined by Albert Einstein. Black hole theory was developed in 1916 by Karl Schwarzschild who gave the first exact solutions of Einstein's equations. In the language of General Relativity, space curves around a massive body, due to the gravitational distortion of space-time. Light follows curved paths (geodesics) in this space-time. If a body is sufficiently massive and sufficiently small, then light from the surface of the body might curve so tightly that it might reach no more than a certain distance from the body. The body would be black, because light would never travel beyond this distance from the body, hence the name *black hole*. In honour of Schwarzschild, this distance is called the Schwarzschild radius of a black hole. No messages can be transmitted from inside the Schwarzschild radius of a black hole to the outside, for this reason, in a picturesque phrase, the boundary between the inside and outside of a black hole is called the event horizon. Any events that occur inside the Schwarzchild radius are over the horizon of visibility from outside.

The event horizon is the closest to the black hole that we can see, and anything that takes place near it (within say several Schwarzschild radii) must show strong relativistic effects. The extent of the Schwarzschild radius is directly related to the mass of the black hole within, as demonstrated in Table 1 for black holes having masses ranging from planets to the equivalent of an entire galaxy. If a galaxy, a planet or whatever could be compressed to a size within the relevant Schwarzchild radius, it would become a black hole.

For most of the 20th century, black holes were a theoretical solution looking for practical problems to solve. They had been shown by theory to be possible, but does nature actually make black holes? Black holes became real with discoveries of new astronomical phenomena. The range of astronomers' vision was extended by an enormous degree with the opening of two new windows on the universe. Radio technology of the Second World War period led to the development of radio telescopes which, in 1963, discovered very distant radio 'stars', which turned out to be galaxies at huge distances. The power sources at their hearts proved to be super-massive black holes. At about the same time, space rockets, also derived from technological advances in the Second World War, made it possible to fly telescopes above the atmosphere and sense celestial emissions that were blocked by air. This opened the X-ray window onto the Universe. Some of the sources that X-ray astronomers discovered proved to be stellar-mass black holes.

An entirely parallel development of science occurred with the theoretical prediction of the existence of neutron stars by J. Robert Oppenheimer and George Volkoff in 1939. Their existence was confirmed with the serendipitous discovery of pulsars in 1967 by the radio-astronomers Antony Hewish and Jocelyn Bell-Burnell.

It has transpired, then, that there are at least two ways that nature makes black holes, on the one hand from individual stars (probably as the result of some types of supernova explosions), on the other hand from dense collections of stars and other material in galaxies.

Stellar-mass black holes

Cosmic X-ray astronomy began almost 40 years ago with a rocket flight above the atmosphere intended to see if there were X-rays coming from the Moon. There were none, but the rocket payload discovered what is still the brightest X-ray source in the sky, known as Scorpius X-1. The launch of the Uhuru X-ray astronomy satellite by NASA in 1970 revealed further X-ray sources, some of which showed periodic eclipses as the source of the X-rays was obscured. The cause of this behaviour proved to be an ordinary star passing in front of the X-ray source as they orbited each other in a binary star system.

The body of observations by Uhuru established the now fundamental model of X-ray sources in which matter is transferred from an essentially normal star onto a compact star, the one in orbit around the other. Such an exchange of material is actually quite common amongst binary star systems, and is an entirely natural result of the processes of stellar evolution, which cause a star to swell up towards the end of its life, as it becomes a so-called red giant. The process of a star accepting infalling matter is known as accretion. Because of the orbital rotation of the star system, the matter cannot fall directly on to the compact star but spirals through an accretion disc. The temperature reached in this process (millions of degrees) is sufficient to produce the X-rays.

The X-rays heat everything in the binary star system, star, gas stream, accretion disc, peripheral matter, which themselves radiate light. The variations around the binary orbit of the X-rays and light provide a rich source of phenomena with which astronomers attempt to decipher the physical processes that are occurring. The study of X-ray binary stars has attracted considerable observational effort, and a corresponding menagerie of species has been uncovered, related to the natures of the compact object and its companion star.

White dwarfs, neutron stars, black holes

The basic source of the X-ray energy is gravitational energy of the matter as it falls onto the compact star. Theoreticians calculate that there are three kinds of stars that are compact enough to produce enough energy in this way. In order of decreasing size and increasing energy, they are white dwarfs (comparable with the size of the Earth), neutron stars (15 km radius) and black holes (kilometre-sized). Astronomers have developed a complex but, in some cases, ambiguous algorithm for distinguishing what kind of compact object is present in any given X-ray binary star, depending on the phenomena that it shows.

The first discriminant is the variability of the brightness of the X-rays. If the X-rays are seen to pulsate regularly, this is interpreted as being caused by the rotation of the compact star. The accreting material funnels onto a particular spot near to the object's surface (due to the intense magnetic field). The spot travels round and round with the compact object as it spins on its axis, so the X-rays from the bright spot regularly appear and disappear.

White dwarfs rotate with periods of minutes or more. Neutron stars rotate with periods of seconds or less, but white dwarfs would break apart (due to centrifugal forces) at such rotation speeds. The X-rays in the bright sources Centaurus X-3 and Hercules X-1, discovered by Uhuru, pulsed with periods of 4.8 and 1.2 s respectively. They could only be neutron stars.

Black holes do not have bright spots that rotate like this, and thus do not produce such regular pulsations. However, the X-rays from material falling into black holes do show fast flickering, without any dominant period. This is an indication of the possible presence of a black-hole. Another key diagnostic to the presence of a black hole is the mass of the X-ray star. This can be measured by studying the gravitational pull of the X-ray star on its accompanying normal star. In favourable observational cases, it is possible to use classical orbital mechanics (exactly as applied to the planetary orbits in the Solar System) directly to measure the masses of both stars in the binary star system, including the compact object itself. The value of the mass indicates what kind of star it is.

As indicated by the table, black holes can be any mass at all, but white dwarfs have a maximum mass of 1.4 solar masses (the Chandrasekhar limit). The value is accurately known, because its underlying physical cause is now well-understood. The maximum value arises from the behaviour of the interior material of the white dwarf star.

For a similar reason, neutron stars, too, have a maximum mass. Its value is not well known because it depends on the physical properties of the nuclear matter of which such stars are made and these properties are poorly determined. They are a primary research goal of experimental physics, and represent one of the challenges of 21st century physics.

It has, however, been possible to make a general estimate of the maximum mass of neutron stars. With various broad assumptions (as broad as the principle of causality, for example) an upper limit to the mass of a neutron star of 3.2 solar masses is often quoted.[1,2] Yet all accurate neutron star mass measurements fall well below 2 solar masses. If, in the future, we succeed in measuring accurately the maximum neutron star mass, it will tell us about the nature of matter at the very highest densities.

To summarize, if a compact star has a mass below 1.4 solar masses, it can be any of the three kinds: a neutron star, a white dwarf or a black hole. If it is between 1.4 solar masses and, say, 3.2 solar masses, it can be a neutron star or a black hole, as far as we know at present. If it is over 3.2 solar masses, it cannot be a white dwarf or neutron star, and must be a black hole.

Cygnus X-1

These two discriminants, variability and mass, were applied in 1971 to the X-ray source Cygnus X-1 by Louise Webster, Paul Murdin and Tom Bolton as the first candidate for a black hole in an X-ray binary system. It became a subject of debate and provoked considerable popular interest. Its X-rays flickered but did not pulsate, so it was not a neutron star or white dwarf. Its mass was determined indirectly, and proved to be in the black hole range.

The compact star in Cygnus X-1 orbits around an optical star, which is a bright supergiant. The orbit is well established, but to use this to derive the mass of the compact object required, in the particular circumstances of Cygnus X-1, an accurate knowledge of the mass of the supergiant. The simplest assumption was that it had the mass of a normal star of the same type. This implied that the mass of the compact star is about 16 solar masses, well over the X-3.2 solar mass limit for a neutron star. This established Cygnus X-1's status as a possible black hole.

However, further studies showed that the underlying assumption about the companion star's mass was weak, because it was not a typical member of its type. The most careful recent analyses[3] of Cygnus X-1 showed that the compact star must be between 4–15 solar masses. This is still over 3.2 solar masses and therefore Cygnus X-1 is, indeed, likely to be a black hole. On the other hand, the lower limit (4 solar masses) of the possible range of its mass is uncomfortably close to the maximum mass for a neutron star. Thus, the mass of the star in Cygnus X-1 was not as well determined as astronomers would like. Extraordinary claims require extraordinarily strong proof. More convincing proof of the existence of black holes came 20 years after the discovery of Cygnus X-1.

X-ray transient stars

Since the 1970s, astronomers have discovered many X-ray binary stars where the mass of the companion star is typical of its type, and the X-ray star's mass would be correspondingly unambiguous. These are X-ray binary stars in which the mass-donor is a cool, low-mass star (usually less massive than the Sun). Unfortunately, this means that the mass-donor is faint (considerably fainter than the Sun). This makes it impossible to see, most of the time, because its own light is completely out-shone by the effects produced by the strong X-ray heating. Figure 1 shows a schematic of a typical low-mass X-ray binary system. However, there is a sub-class of low-mass X-ray binary stars, known as the soft X-ray transients. As their name implies, they are not steady sources of X-rays, but undergo transient, rare, dramatic outbursts of soft (low energy) X-rays. The transient outbursts last a few months and are typically separated by decades. This curious behaviour provides the right circumstances to read the full story of what is going on.

The X-ray outburst proves that there is a compact star in the system, accreting during the outburst period some of the material from the ordinary star that it orbits. Afterwards, the system returns to quiescence and the intense glare from X-ray heating subsides. The X-rays having drawn attention to the binary star in the first place, and having died away, it becomes possible to observe the ordinary star directly, even though it is faint and the observations are a struggle. It is worth while making this effort, because it is possible to determine the mass of the compact star.

A0620–00 was the first example observed in this way by McClintock and Remillard.[4] Its mass was measured to be 2.9 solar masses or more, so the nature of this particular example remained somewhat ambiguous, but the accuracy achieved demonstrated the power of the technique. Shortly afterwards, the mass of the compact star in the soft X-ray transient V404 Cygni was measured by my

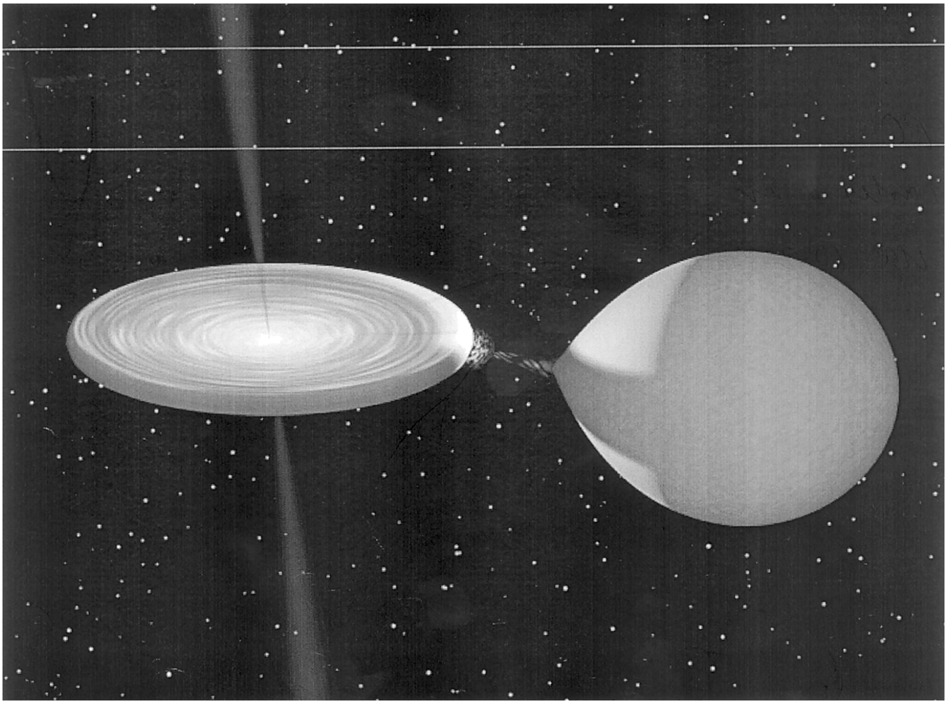

Figure 1. Schematic diagram of the essential components of a low-mass X-ray binary in which mass is transferred from a cool, low-mass star (right) onto either a neutron star or black hole, via an accretion disc (left). If the conditions are right, a jet is ejected as shown. (Diagram supplied by Dr Robert Hynes, University of Southampton.)

colleagues and me with the (then new) William Herschel Telescope on La Palma as at least 6.1 solar masses, putting it firmly in the black hole range.[5] This lower limit to the compact object mass in V404 Cygni is totally secure, as it makes no assumptions about the nature of the two stars. V404 Cygni was hailed as the clearest example of a black hole known up to that time.

In general, the more relevant information that a scientist can put into an analysis the more constrained the problem is and the more definitive the outcome. By correlating use of the largest optical and infrared telescopes, and X-ray telescopes in orbiting satellites, astronomers can, sometimes, obtain a full description of some soft X-ray transients.

In the last decade, 17 X-ray transient stars have been analysed and their masses determined. Three are neutron stars and 14 are black holes on this criterion. They have masses of 10 solar masses, more or less. Such a black hole is called a stellar-mass black hole, and was made by a supernova explosion, at the end of the life of a star of mass several times larger. Most of the mass of the star exploded into space, but some imploded to make the black hole. On our own scale, stellar-mass black holes are impressive, but they are puny compared with super-massive black holes in galaxies.

Super-massive black holes in galaxies

In the early 1960s, the discovery of quasars (quasi-stellar radiosources), and their identification with what looked like ordinary stars, presented a major problem for theorists to solve. This was because they were found to be the most distant objects then known and, therefore, to be seen as stars, they had very high luminosities. They ranged up to a hundred times the output of an entire galaxy!

It transpired that quasars were the brightest members of a group of objects called active galactic nuclei or, more commonly amongst astronomers, simply AGN. The ‘active’ tag is used because they are highly variable, on a time scale of days, hours or even minutes. Radio astronomers used networks of radio telescopes to image AGN at high resolution by the technique of VLBI imaging (see the accompanying article by Smith). This confirmed that all the energy of the AGN was produced from a volume comparable in size to our Solar System or smaller. The output from the volume of space around our Solar System is one solar luminosity; from the same volume in the active region of a quasar the luminosity is as much as 10 thousand million solar luminosities!

The super-massive black hole in an AGN is surrounded by an accretion disc that is fed by material from the host galaxy, as demonstrated schematically in Figure 2. The material could have originated as interstellar material, or could even once have been entire stars, disrupted by tidal forces of the black hole and swallowed into the surrounding accretion disc.

This scenario describing the central engine of a quasar and the phenomena associated with it was actually constructed about 30 years ago.[6,7] However, all the evidence supporting the picture was indirect. Furthermore, there were competing models. What was needed was direct evidence for the presence of a black hole, and its mass. Determining that mass accurately was a goal that eluded observers until the arrival of the Hubble Space Telescope (HST).

The black holes in M87 and NGC4258

At a distance of 50 million light years in the centre of the Virgo cluster of galaxies, M87 is the best nearby example of an AGN. Once the refurbished Hubble Space Telescope gained its high resolution capability, it was possible to see the accretion

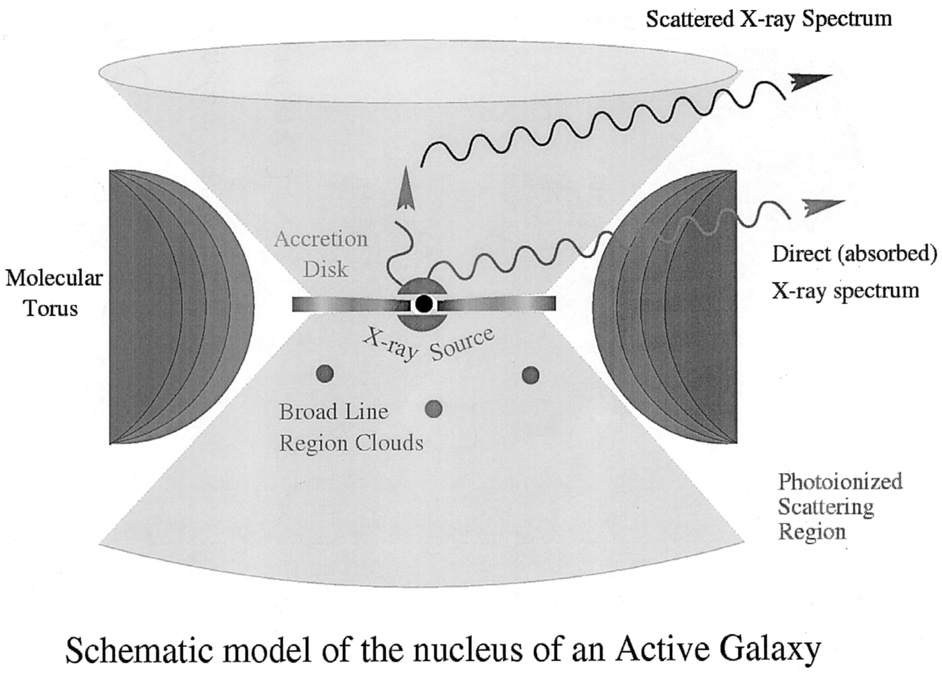

Figure 2. The currently accepted model of an AGN in which the super-massive black hole and its accretion disc (centre) are surrounded by a giant torus of cooler material. This entire structure would have a scale of barely half a light-year. (Image provided by Dr Christine Done, Durham University.)

disc surrounding the nucleus of M87. It extended out to about 250 light years from the nucleus (Figure 3).

The HST was able to measure the rotation of the accretion disc from its furthest extent down to 10 light years. Although this is at a considerable distance from the nucleus, this was by far the closest that anyone had approached a black hole in this way. Its mass was determined at 3.2 ± 0.9 billion solar masses.[8]

To probe closer to the putative black-hole nucleus than the limiting spatial resolution of HST requires the much higher resolution possible using VLBI. Such an opportunity arose when radio emission was discovered from another active galaxy, NGC4258.[9] The VLBI network imaged the central region of the galaxy with a mapping resolution equivalent to the apparent size of an astronaut on the Moon as viewed from Earth! The radio observations gave similar information to that of HST on M87, but probing even closer to the AGN core. Again, the measurements showed the behaviour expected from material orbiting a

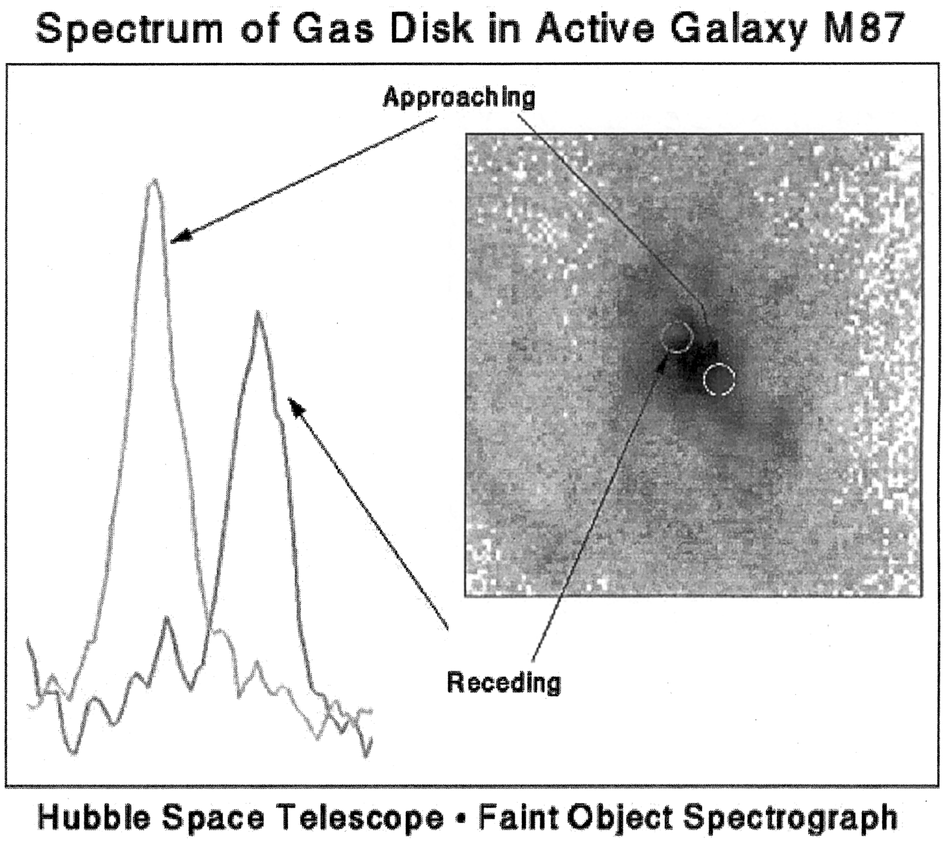

Figure 3. HST image of the very central regions of M87, which reveal the disc of material surrounding the core. Spectra of this disc show that one side is receding, the other approaching, exactly as expected if this disc is orbiting a central object of approximately 3 thousand million solar masses (STScI public archive).

super-massive black hole of mass 36 million solar masses, all concentrated within a radius of 0.8 light year.

The black hole in our galaxy

Most galaxies are not quasars although astronomers believe that most or all have black holes at their centres. They argue that most quiescent black holes at the centres of galaxies are starved of accretion fuel. This might be because their galaxy has settled down to regular circular rotation and material only falls on to the black hole if the galaxy is disturbed in some way. To test this plausible guess, over the last 15 years astronomers have searched for black holes in nearby, otherwise normal, galaxies.

The best example has now been found in the nucleus of our own Galaxy! At its very centre is a weak radio source called Sagittarius A*, the location of our Galaxy's black hole. In the last decade, two groups, led by Reinhard Genzel[10] and Andrea Ghez, have repeatedly imaged the stars that cluster around Sagittarius A*. Over ten years, they have seen the stars move on the sky relative to Sagittarius A*. From these observations, they have determined the orbits of individual stars and the mass of what they orbit about. It is of mass 2.9 ± 0.4 million solar masses, and is contained entirely within a radius of less than 1 light month. Our own black hole is not the most massive one known, but it is now the most accurately determined mass of a compact galactic nucleus.

All galactic nuclei that have been measured, M87, NGC4258, our own Galaxy, and others, show a large mass within a small volume. This indicates that galactic nuclei are black holes (cf. Table 1). However, none of these observations gave any specific information on the nature of that mass.

Effects of strong gravity

None of these observations of compact objects that have large masses within small volumes actually probe the physics of the processes that must be occurring close enough to the objects themselves. The masses of AGN are large, but do their properties depend on General Relativity? If AGN are really black holes, we will only know by looking at what is going on near the event horizon, where perceptible relativistic effects occur. Does any emission come from that close?

Close to the event horizon, at the inner edge of the accretion disc, the orbiting material is moving at close to the speed of light and hence is extremely hot. The Japanese X-ray astronomy satellite, Ginga, observed very hot material in some AGNs.[14] Its key diagnostic was X-ray emission from highly ionized iron in the gas of the accretion disc. The high speeds, the high temperatures, and the violent atomic collisions that were the result had stripped the iron atoms of many of their electrons. This indicated that the iron emission came from near the event horizon.

The spectrum of the iron emission is influenced by a number of physical processes in the space-time environment near the black hole. These include processes peculiar to Special and General Relativity. Matter in orbit under Newtonian conditions shows symmetries. For example, accretion disks, seen obliquely, appear as ellipses symmetric on left and right, and their fronts are similar to their backs. Time runs as quickly for the matter in the accretion disc as for us. But under Special and General Relativity the symmetries break down because the behaviour relative to the observer is added into consideration.

Space-time distorts from the simple symmetrical properties that are typical of everyday experience.

Approaching material (on the right, say) looks different from receding (on the left). The back of the disc is viewed over the black hole, so looks different from the front. Time runs more slowly in the strongest gravitational field nearest the black hole, and alters the clocks in the iron atoms there that set the frequency of its emission, so the iron emissions are different from ones in terrestrial laboratories. The result of adding the relativistic effects to a purely Newtonian starting point is to break the symmetry of the appearance of the disc in ways that are very characteristic of relativity, and act as signatures of strong gravity.

The Ginga satellite did not have the capability to investigate these relativistic effects in any detail. This opportunity fell to the Japanese ASCA satellite (launched in 1994) which had far superior X-ray detectors, supplied by European industry and universities. The data from the ASCA satellite of MCG-6–30–15 show strong asymmetry, indicating the influence of relativity. The shape of the profile is not something that one can imagine arising by chance. The fit to the data of a complex mathematical expression derived from relativity is surprisingly good. The best fit shows that the material closest to the black hole is orbiting at 0.3 the speed of light at a distance of only 6 Schwarzchild radii. It was behaving in a highly relativistic way. For the first time, the case that black holes exist in AGN had been bolstered beyond purely circumstantial evidence of mass and size. A distinguishing physical characteristic of black holes as phenomena of General Relativity, namely the effects of strong gravity, had been identified (see for example, Ref. 11 for a full discussion).

The data were the result of two weeks' observing by the ASCA satellite. It must have cost of the order of 1 million euros to obtain, a cost fully justified by the sensational result. Sceptics might like the fit of the data to be even better, but, given the reality of the limited resources in the ASCA satellite, and the heavy competition for access to it, that would be unlikely to happen with ASCA. However, recently launched, considerably larger and even more sensitive X-ray satellites, NASA's Chandra satellite – named after the Chandrasekhar of the white dwarf mass limit – and ESA's Newton Observatory – named after Isaac Newton – are probably observing AGN as I write. They are probing the detailed X-ray emission processes occurring very close to the event horizons of black holes, and the physics of general relativity that AGN reveal. X-ray spectroscopy is a new frontier of high-energy astrophysics.

Intermediate mass black holes in nearby galaxies

Stellar mass black holes exist in X-ray binary stars. They were made by supernova explosions in one of the binary star components. Super-massive black holes exist in AGN. They were made, apparently, by processes early in the history of the universe, which accumulated millions or thousands of millions of stars into the centres of the galaxies. Are there any other processes by which nature makes black holes? There is a clue that the answer might be yes, there are indications that nature makes black holes of a mass intermediate between these two extremes. The evidence comes from the new recognition of a population of bright X-ray stars. X-ray images of nearby galaxies, obtained by NASA's Einstein Observatory about 20 years ago, provided the first look at the normal population of X-ray binaries and supernova remnants in each galaxy. In these first images, it was noted[12] that some galaxies contained sources of unusually high luminosity, apparently much brighter than the brightest sources in our own Galaxy, but not as bright as AGN, and not central to the galaxies. With the equipment then available, it was not possible to tell whether these sources were individual high luminosity sources of an interesting kind or unresolved groups of ordinary X-ray sources.

The Chandra X-ray Observatory in 1999 provided X-ray imaging capabilities that are, for the first time, comparable to the best ground-based optical imaging. These have revealed that many of these sources are indeed point-like, and highly variable and hence are very likely to be individual. An example is shown in Figure 4, an image of the galaxy M82 taken by Chandra. The brightest source (which is not central to M82 and is not a weak AGN kind of black hole) is variable and seems to be a single X-ray binary star. Since this and similar sources are ten times more luminous than ordinary black hole X-ray binary stars, then if they are accretion-powered black holes, their masses must be in the region of 100 solar masses.

This would mean that it must be possible to produce black holes of masses intermediate between 10 solar masses and a million or a billion solar masses. There may therefore be more than two ways in which nature makes black holes. The third way might possibly be some undiscovered outcome of the life of very massive stars. The whole situation is, however, a bit puzzling because individual stars have masses that range only up to about 130 solar masses. Such big stars are rare. It seems a lot to ask that virtually all the mass of the rare stars should have imploded to make several black holes of 100 solar masses. So, in astronomy as in politics, the third way is not exactly clear and therefore attracts interest.

Conclusions

The dramatic advances in the determination of black-hole parameters for both X-ray binaries and galactic nuclei have come about in the last 10 years as a result of high powered astronomical technology, both in space (large X-ray telescopes

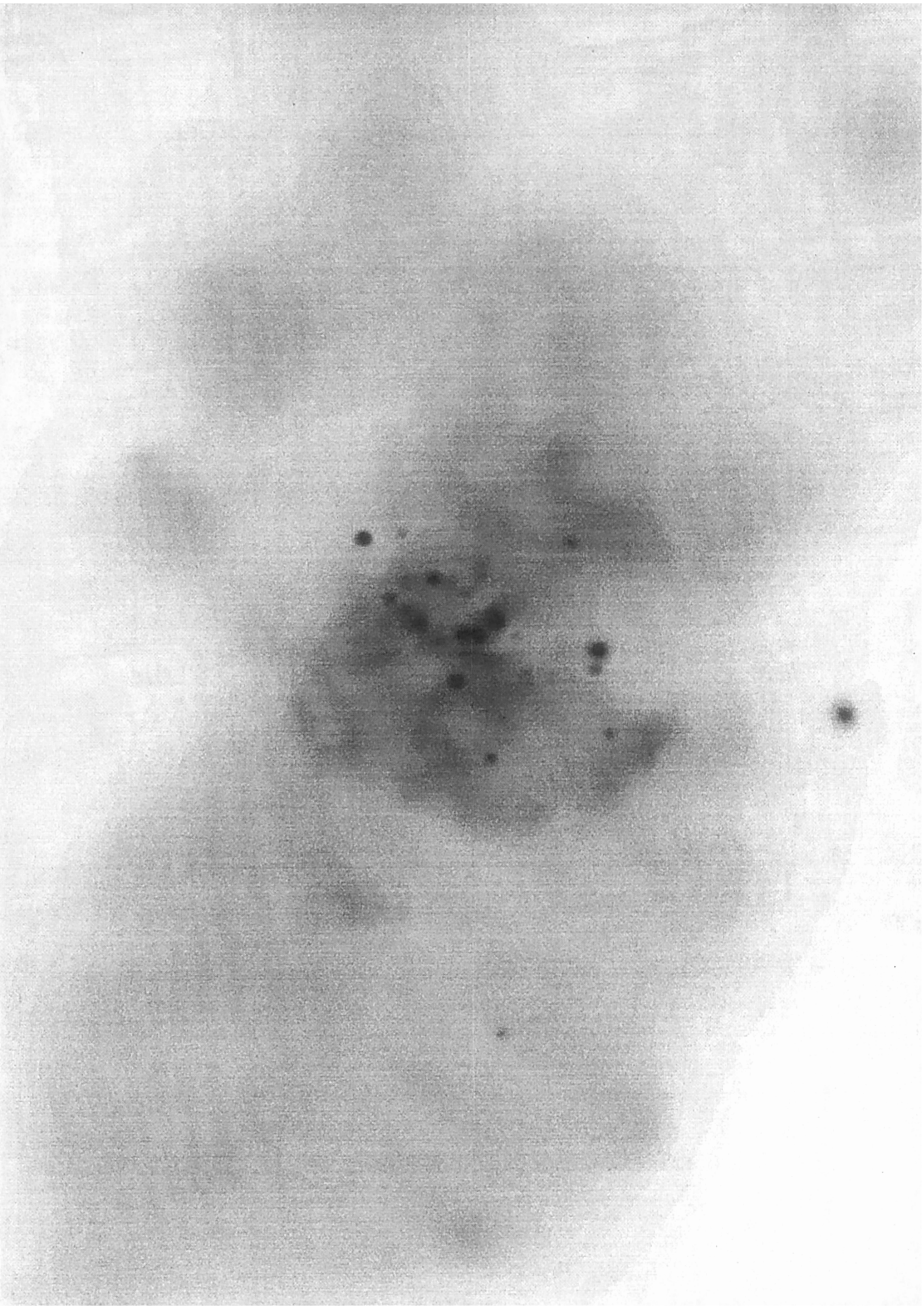

Figure 4. This superb Chandra X-ray image of M82, the nearest starburst galaxy, reveals many bright X-ray sources, which are a combination of supernova remnants and X-ray binaries. The brightest source is variable and hence likely to be an X-ray binary, but its luminosity implies that it has a mass of more than 100 solar masses (Chandra public archive).

with advanced specification detectors), and on the ground (even larger optical and infrared telescopes mounted at the best sites in the world, and radio telescopes the size of the Earth). This technology has put black holes at the heart of several astronomical objects and moved them from the status of theoretical possibility to established phenomena. There are signs that there are further kinds of black holes to identify. Future space missions, such as ESA's XEUS, intended to be assembled in the International Space Station, are now being planned with even greater capabilities (in terms of spectral and spatial resolution). The intention is to make new advances in fundamental physics from studies of the strong gravity field that exists just outside a black hole's event horizon. This is indeed a truly exciting prospect.

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