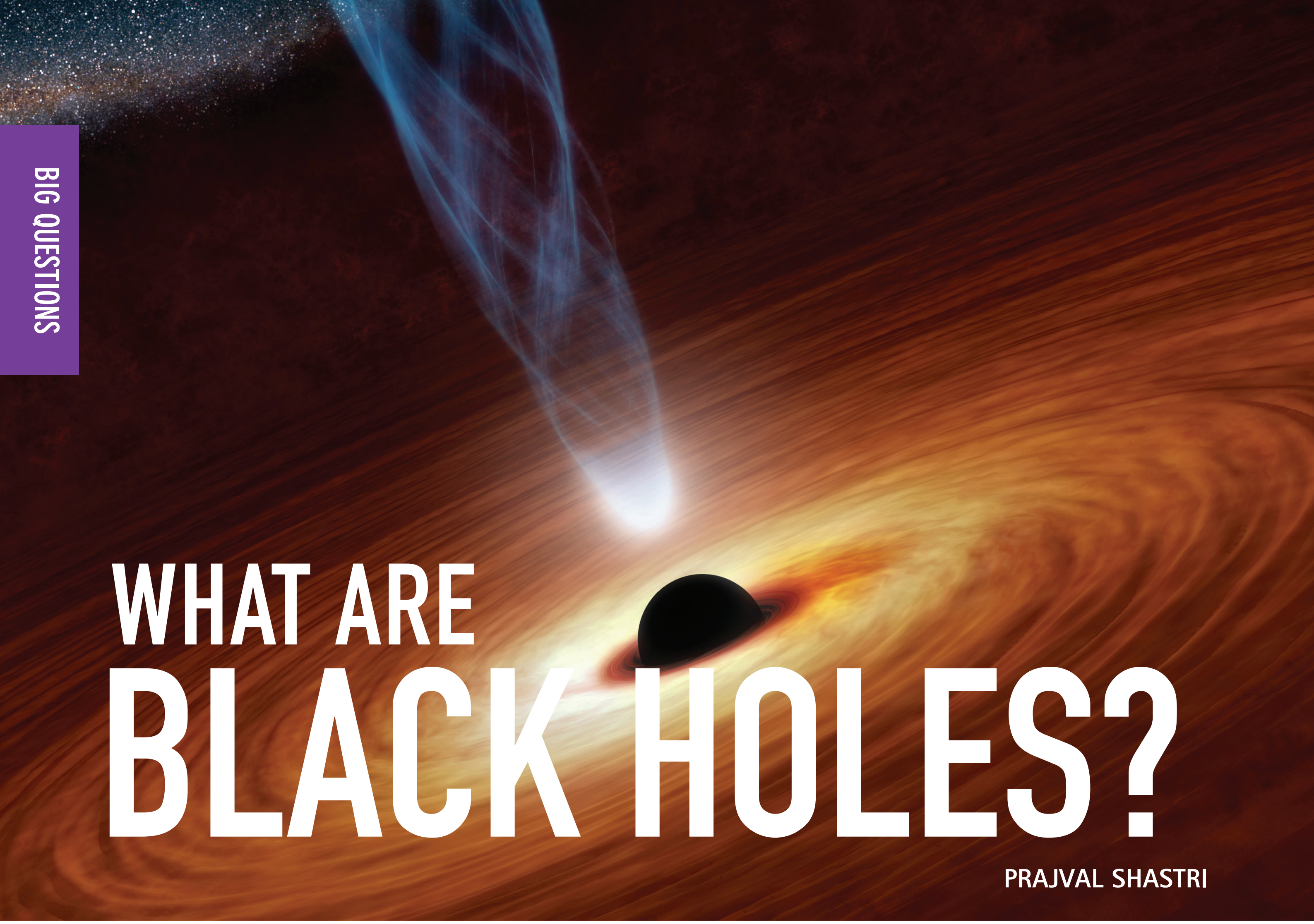


WHAT ARE BLACK HOLES?

PRAJVAL SHASTRI

In the very hearts of galaxies, like our Milky Way, lurk giant black holes that sometimes evolve into monstrous powerhouses of light. How do we know that they exist? How are they born? How do they grow? Are they important in the 'big picture'?

Step outdoors under a dark night-sky and a serene sight presents itself. About 3000 stars, a couple of planets, maybe a moon too, enchant us. Once in a while, at the right latitudes, so does a galaxy such as the Andromeda or the Magellanic Clouds. The most breathtaking of all, though, is our very own Milky Way.

The serenity of the night sky is deceptive. Each of these thousands of pin-points of light (or stars) is a cauldron of burning nuclear fuel, just like our sun. The bluer pin-points are even hotter and more massive than our relatively 'mid-range' sun. Our understanding tells us that the lives of stars, especially massive ones, end in an enormous explosion (called a **supernova**). The supernova leaves behind a 'remnant' object, which for stars many times the mass of our sun, will eventually become a black hole.

What are black holes?

Black holes can be thought of as chunks of space in which the force of gravity is so strong that even light cannot escape from them.

They were first referred to in the late 18^{th} century by the English clergyman John Michell. Michell conjectured the existence of objects so massive that their **escape velocity** (see **Box 1**) would equal the velocity of light. Einstein's theory of General Relativity, published in 1915, put these ideas on a firm and rigorous footing. In a paper published a few months later, Karl Schwarzschild took Einstein's theory forward to predict objects that would behave in this way. In 1967, the physicist John Wheeler coined the term 'black hole' to describe them. In 1970, the Indian physicist C. V. Vishveshwara showed that black holes were stable — a property critical to our ability to observe them.

Box 1. What is escape velocity?

It is the speed that an object needs to have in order to escape the gravitational field that it is in. For e.g., we know that the escape velocity on the surface of the earth is 11.2 km/s. This means that the velocity of any object (like a satellite or a cricket ball) hurled upwards needs to exceed 11.2 km/s for it to leave the earth, and not have the earth's gravity pull it back.

How do we know they exist?

No light can come from a black hole — this is, in fact, why they are called 'black'! This means that we cannot 'see' them; at least not directly. Nor are black holes being formed or created in any human-built laboratory of any kind on earth. However, with our sky being a universal laboratory, there are other fascinating possibilities to explore the properties of black holes. These include:

(a) Circumstantial evidence: This has led us to suspect the existence of giant black holes in the heart of a small fraction of galaxies in the universe.

The gravitational field in the close vicinity of a black hole is extraordinarily strong (see **Box 2**). Therefore, any object (gas, or even stars) coming into its immediate neighbourhood will swirl right into it at enormous speed, causing the black hole to grow. The speed of the object swirling in generates a friction that causes the black hole to heat up to exceedingly high temperatures. Since the gravitational energy harnessed in this event is enormous, the resulting power that is radiated out could be a few trillion times the power radiated from our sun! Thus, these 'munching' black holes also 'shine' brightly. In reality, it is, of course, their close environs (and not the black holes themselves) that shine.

Such black holes are like powerful beacons that can be spotted at enormous distances. Even very early telescopes (from the 1960's) saw these powerful beacons of light. Indeed, the 'Gargantua' that dazzled us in 'Interstellar' (see **Fig. 1**) is exactly such a growing, shining, fictional black hole. The mass of these 'giant' black holes, referred to by astrophysicists as 'supermassive', is measured in $M_\odot$ (i.e., the mass of our sun, which is 2×10^{30} kg) — a unit that astrophysicists tend to use for all objects larger than the sun (see **Glossary**).[1,2] The only way such power can be explained is if the strong gravity around giant black holes is being harnessed. As a result of this circumstantial evidence, the idea of giant black holes became quite

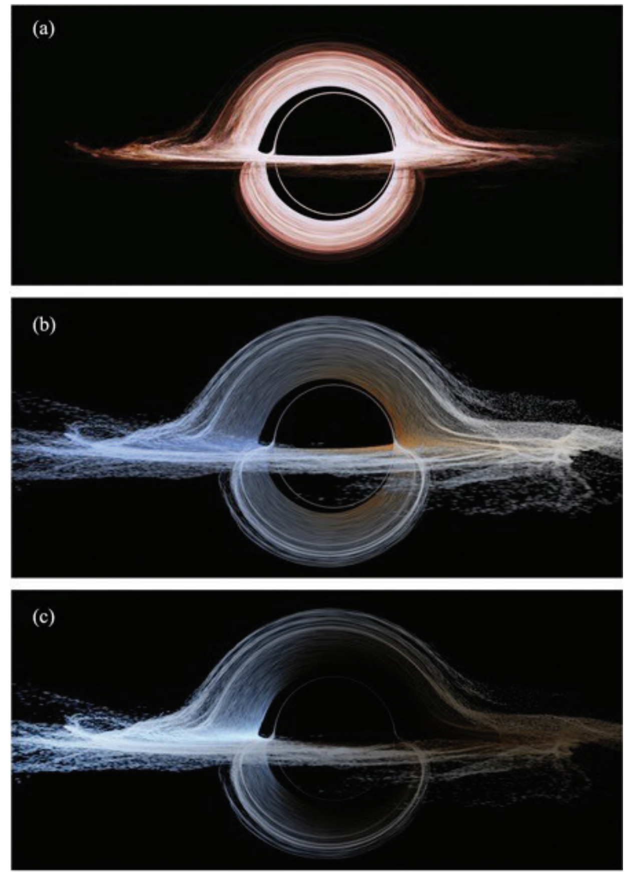


Fig. 1. A computer-generated image of the fictional growing giant black hole 'Gargantua' that featured in the science-fiction movie 'Interstellar'. This image shows how such an object would appear to an observer in visible light. The computer code, called Double Negative Gravitational Renderer, incorporates what physicists know about the growing black hole and the effects of strong gravity around it.

Credits: James et al 2014. URL: http://iopscience.iop.org/article/10.1088/0264-9381/32/6/065001/meta;jsessionid=6234B192EDE9A0CD2BD9C6370D4643E1.c4.iopscience.cld.iop.org. License: CC-BY.

Box 2. A black hole's gravitational field:

The super-strong gravity of black holes (that makes them different from regular objects of comparable masses) can be felt only in their close neighborhood. Since black holes are very small-sized for their mass, it is physically possible for objects to closely approach them. For e.g., if our sun were to turn into a black hole tomorrow, its entire mass would have to collapse into a radius of ~ 3 km. Hypothetically, if this were to happen, it would make no difference to the gravitational force that is felt due to the sun on earth. Contrast the radius of 3 km, however, with the current radius of the sun, which is 695,700 km. The closest that an object can approach the sun (without actually entering it) is, therefore, 695,700 km, which is where the gravitational force due to the sun will be maximal. On the other hand, if the sun were to turn into a black hole, an object could approach as close as a few kilometres from its centre. At this distance, the object would experience a gravitational force (from the same mass) that is ~50 billion times higher (since gravitational force increases inversely with the square of the distance). Clearly, even in the proximity of a hypothetical 'solar' black hole, at say a distance of a few thousand kilometres, the gravitational force would be enormous. Any matter reaching the close neighborhood of a black hole, therefore, would be inexorably sucked in, eventually plunging into the black hole.

Box 3. Identifying black holes by their mass:

This method can be understood by using the analogy of the solar system. We know that planets of our solar system move around our sun, driven by the sun's gravity, in roughly circular orbits. Our understanding of circular orbits and gravitational force is encapsulated in Kepler's law. This law tells us that the square of the speed (v) of a test particle of negligible mass (in this analogy, a planet) is directly proportional to the heavy mass (M) around which it orbits (in this case, the sun), and inversely proportional to its distance (r) from the heavy mass:

$$v^2 = \frac{G\,M}{r}$$

Therefore, the mass of the heavy object can be computed if the speed of the test particle and its distance from the heavy mass can be measured.

Fig. 2. Our Milky Way as photographed from Hatu Peak, Narkanda, Himachal Pradesh, India.

Credits: Ajay Talwar and Pankaj Sharma.

entrenched in astrophysics lore, even though direct evidence for black holes came much later.

(b) Elliptical star orbits at the centre of our Milky Way and other galaxies beyond: Another method to hunt for black holes is based on Kepler's Law. It involves the search for dark objects that can be demonstrated to have such a high mass that they **must** be black holes (see **Box 3**). This search, lasting several decades, has yielded about 20 black holes within our Milky Way, and many, many more beyond it.[3]

Our Milky Way contains over a billion stars. The stars in this part of the galaxy are about 26,000 light-years (see **Glossary**) away from us. Between these stars are vast spaces that are empty but for a tenuous distribution of dust particles. These particles are, nevertheless, numerous enough to dim the light from the stars behind them, like a fog. Consequently, the parts of the Milky Way with the densest distribution of dust particles appear as dark patches in photographs (see **Fig. 2**). These dust particles also enshroud the centre of the Milky Way. Therefore, to peer into the centre of our cosmic village, we need light other than that in the visible range — infra-red light, for instance. If the same piece of sky is repeatedly imaged over several years, one can begin to discern the movements of some of these stars by shifts in their positions in the sky. These shifts can also be used to compute the speed at which these stars move.

Two teams of scientists have studied the stars at the centre of the Milky Way in this manner for many years now.[4,5] One of these teams is led by Andrea Ghez from the University of California, Los Angeles (USA), and the other is led by Rheinhardt Genzel from the Max-Planck Institute for Extraterrestrial Physics, Germany. Their painstaking investigations show that some of these stars are moving at speeds that exceed 1500 km/s and have orbital periods of the order of 20 years (see **Fig. 3**).

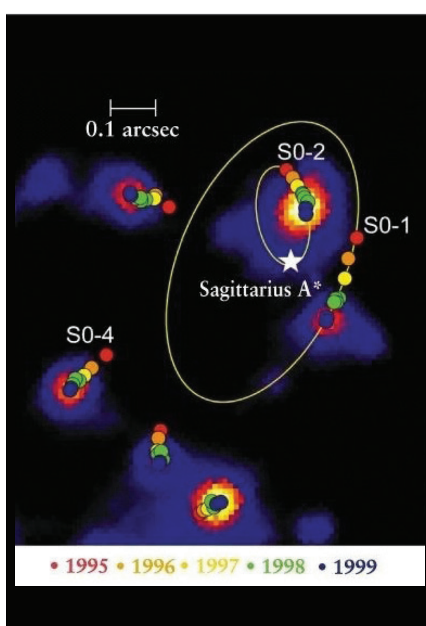


Fig. 3. The black hole at the centre of the Milky Way. The coloured patches represent images of stars in the year 1999. The circles represent the positions of some of these stars in 1995, 1996....1998, colour-coded by the year (see legend). The ellipses represent the orbits of two of these stars, labeled S0-1 and S0-2, extrapolated from the measured change in their positions. The white star-shaped symbol represents the position of a 'dark object' that must exist in order to gravitationally drive the moving stars. The white bar labeled 0.1 arcsec gives the angular scale of the image (for comparison, the size of the moon is 30 arcminutes). At the centre of the Milky Way (which is about 26,000 light-years), 0.1 arcsecond (see **Glossary**) = 4.6 light-days.

Credits: These images/animations were created by Prof. Andrea Ghez and her research team at UCLA from data sets obtained with the W. M. Keck Telescopes. URL: http://www.galacticcenter.astro.ucla.edu.

Assuming that a heavy (but, obviously dark) object is driving these stars in their orbits, the mass of this driver is computed to be four million times the mass of the sun! The position of the dark object can be fixed based on the fact that it is the common focus of all the observed elliptical star orbits. The distance of the star (labelled SO-16) that is seen to approach the closest to this position (see **Fig. 4**) gives us an upper limit to the size of the dark object. If the dark object were bigger than this distance of closest approach, we would have seen evidence of a collision between star SO-16 and the dark object. That such a collision does not occur suggests that the inferred large mass of the dark object occupies quite a tiny space. This proves that the object is, in fact, a black hole.

This method cannot be used to look for black holes in other galaxies because even our 'nearest' neighbors are a few hundred million light-years away from us. At such large distances, even with our best telescopes, individual stars in these galaxies remain indistinguishable. One way of working around this is to look at atomic lines from individual stars in other galaxies. These lines are Doppler-shifted (see **Box 4**) towards blue or red, depending on whether the stars are moving towards or away from us. Although the instruments we have at present cannot separate these lines in a spectrogram, their spread in the blend they appear as gives us a quantitative measure of the spread in the speeds of the stars that form them. When the speed of stars is directly dependent on the mass of a central giant black hole, its approximate mass can be estimated through Kepler's Law.

(c) Ripples in spacetime: In a spectacular discovery in 2015, scientists detected the presence of black holes (with masses ranging from 8-60 times the mass of our sun) by the ripples they create in spacetime.[6] Measurements of gravitational waves from this experiment (by the Laser Interferometer Gravitational-Wave Observatory or LIGO) were perfectly consistent with predictions made by Einstein's theory and its later developments (including those by C. V. Vishveshwara).

How are giant black holes formed?

We have previously alluded to massive stars leaving behind black holes at the end of their lives. That ripples in spacetime from merging black holes have been detected for the third time hint at the merging of black holes being a fairly common phenomenon in the cosmos. Are the giant black holes of over a million $M_{\odot}$ found in the centres of galaxies the result of these repeated mergers over the lifetime of the universe? Let us examine this argument.

Calculations show that the most massive black holes that can be formed from stellar death cannot exceed about 100

Box 4. What is Doppler shift?

When the source of a wave moves towards (or away from) an observer, the frequency of the wave seems to increase (or reduce). This is known as the Doppler shift, after the physicist Christian Doppler who first proposed it. An oft-quoted everyday example is the increase (or decrease) in the pitch of the sound of a horn from a moving vehicle as it approaches (or recedes) from an observer. A similar effect occurs when a light source approaches or recedes from an observer, although this is noticeable only at very large speeds and/or very precise measurements of its wavelength.

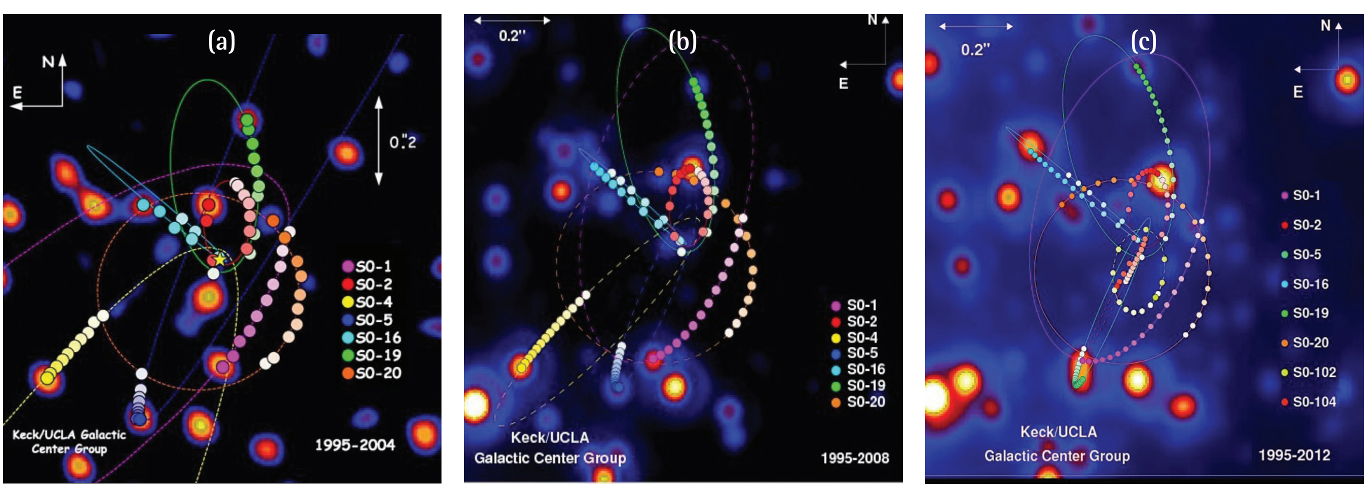


Fig. 4. Stars at the centre of the Milky Way are pushed outwards. The three panels, from left to right, contain measurements of these stars during the periods **(a)** 1995-2004, **(b)** 1995-2008, and **(c)** 1995-2012 respectively. In each case, the latest positions of the stars are visible in the image as coloured splotches, which represent the actual infra-red images of the stars. The changing positions of these stars with time are shown as coloured circles for clarity. Their progression with time is indicated by increasing saturation of the colour of these circles. Some of the stars can be clearly seen to make elliptical orbits around a common point marked by a yellow star symbol in the centre of panel **(a).** The orbit and positions of star SO-4 (circles coloured yellow) have not been shown in panel **(c)**, but it is clearly moving far away from the centre.

Credits: These images /animations were created by Prof. Andrea Ghez and her research team at UCLA from data sets obtained with the W. M. Keck Telescopes. URL: http://www.galacticcenter.astro.ucla.edu.

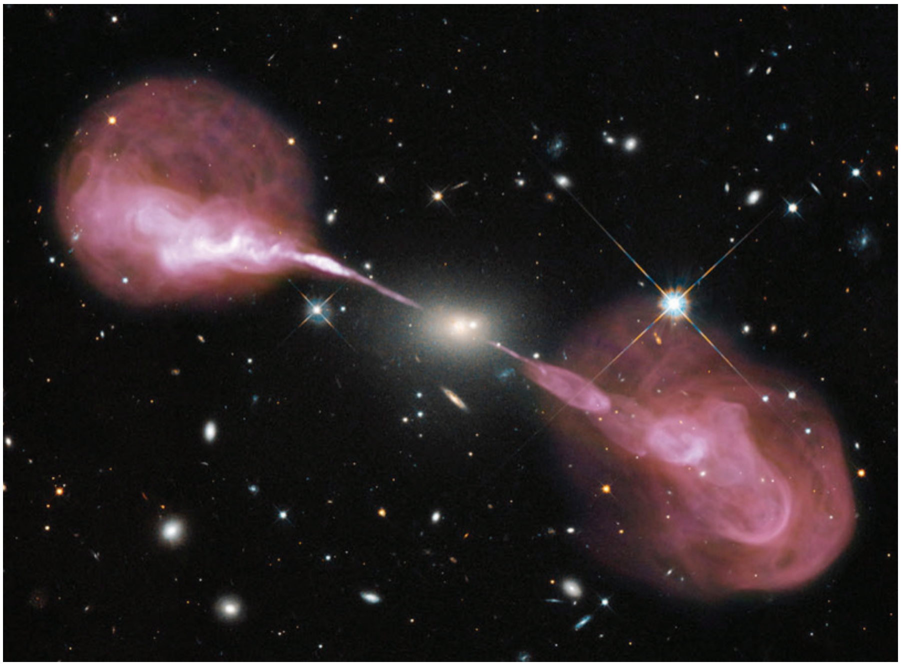


Fig. 5. The growing giant black hole Hercules A. Located at a distance of about 2 billion light-years, its radio image shows the twin-jets of plasma (false-colour image in pink) reaching out to nearly a million light-years. This is overlaid on the image of the field in visible light, showing the galaxy harbouring the giant black hole that squirted out the twin jets.

Credits: NASA, ESA, S. Baum & C. O'Dea (RIT), R. Perley & W. Cotton (NRAO/AUI/NSF), and the Hubble Heritage Team (STScI/AURA). URL: http://www.nrao.edu/pr/2012/herca/. License: CC-BY.

$M_\odot$. The largest one to be observed (by LIGO) to date is of about 60 $M_\odot$. Clearly, then, building giant black holes by merging remnant black holes from stellar death will need mind-bogglingly large amounts of time.

However, astoundingly, more than a handful of growing giant black holes, also known as **quasars,** have been discovered to exist from when the universe was less than a billion years old (the current age of the universe is 13.8 billion years). These black holes appear to have masses of not just a million $M_\odot$, but a billion $M_\odot$! Clearly, even with repeated coalescence with the largest possible black holes left behind from the death of stars, a billion years would not give enough time to build a giant black hole of a billion $M_\odot$. Therefore, the idea that extremely large clouds of gas in the very early universe may have directly collapsed into large black hole seeds of about 10000 $M_\odot$ is beginning to gain ground.[7] These black hole seeds may have coalesced with each other to build giant black holes.

Giant black holes may have continued to grow by accumulating any swirling matter that crept into their neighbourhood. Many of these growing black holes are known to squirt out twin-jets of plasma that shine in radio light. In about 15% of these cases, these twin-jets are launched at speeds very close to the speed of light, and reach distances of many million light-years into extragalactic space (see **Fig. 5**).

Giant black holes can also grow by coalescence, like with the tinier cousins discovered by LIGO, if the galaxies that they inhabit come together. In fact, there is strong evidence that galaxies often merge to form bigger galaxies (see **Fig. 6**). Computer simulations of the physics of such interactions predict that the central black holes of merging galaxies will also eventually coalesce. This coalescence is predicted to create

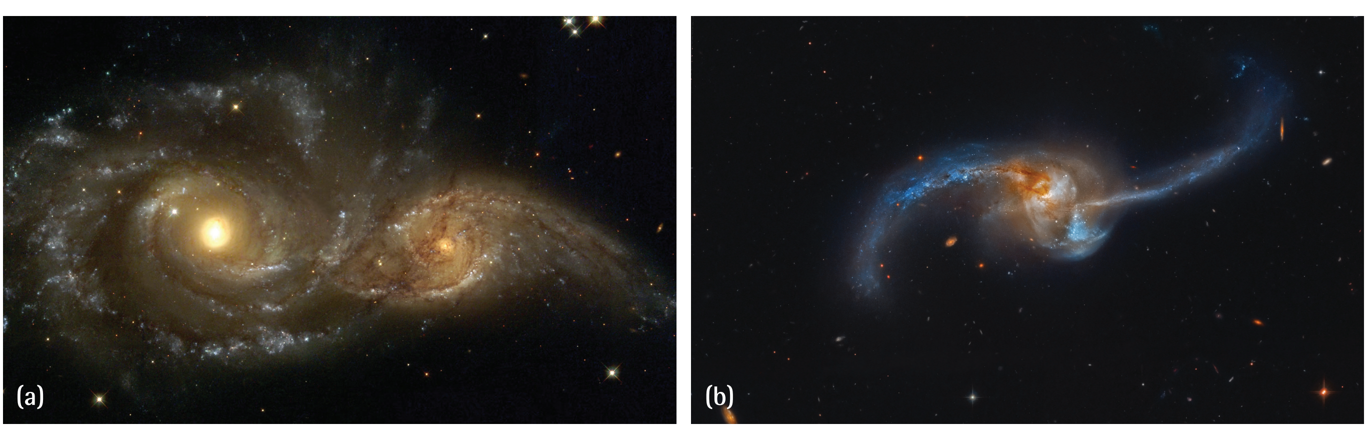


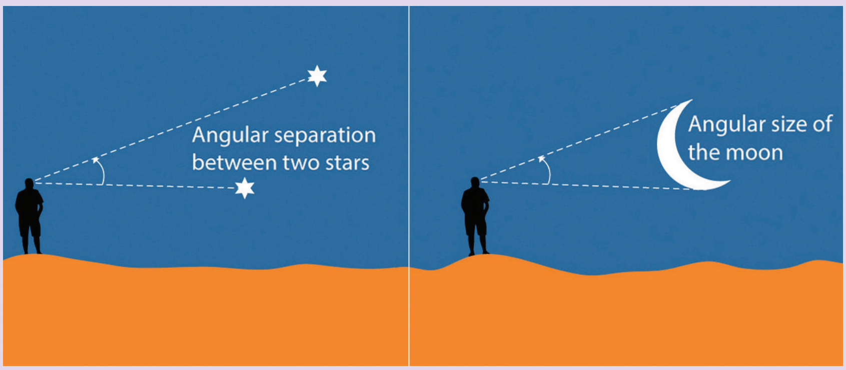
Fig. 6. Examples of merging galaxies. (a) A pair of galaxies, NGC2207 and IC163, on a collision course. **(b)** A merging galaxy — NGC2623. The system to the right is clearly further along in the merging process than the pair on the left. Therefore, what were formerly spiral arms of one of the original galaxies can be seen to have been 'pulled' apart, and the merging complex in the middle has begun to look like one galaxy, though rather 'disturbed'. The central giant black holes of these erstwhile separate galaxies are eventually expected to merge.

Credits: Hubble Space Telescope, NASA. URL: (a) http://hubblesite.org/image/1627/news_release/2004-45 & (b) https://apod.nasa.gov/apod/ap121019.html. License: with permission for free use.

Glossary:

Light-year: a unit of distance in astrophysics used to refer to the distance that light can travel in a year (~ 9.5 trillion kilometers).

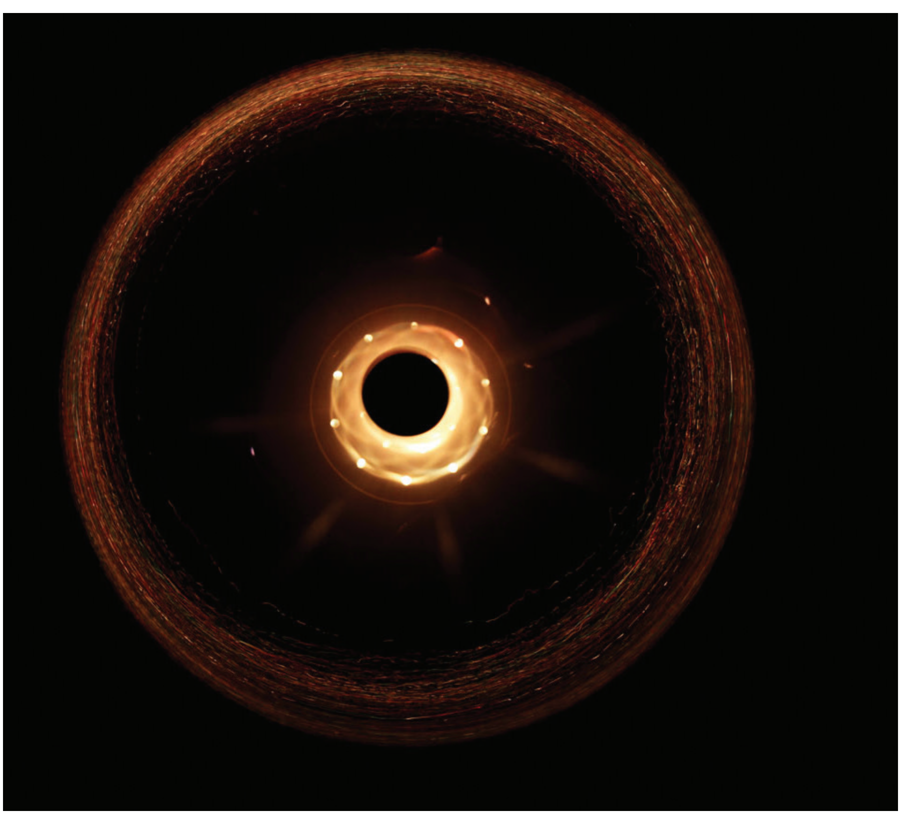
Arcsecond: It is common in astronomy to measure sizes of objects in the sky (or the separation between objects) in angles (vs. using physical units of distance or size, such as kilometre). This is because making such measurements in physical units is a complex process that requires a lot of other kinds of information. In contrast, the 'angular sizes' and 'angular separations' of objects in the sky are directly measurable from an image, or, if large enough, even by visual observation.



Calculating arcminutes.

An object is said to have a size of 1 degree if it subtends an angle of 1 degree at the eye, and an angular size of 1 arcsecond if it subtends an angle of one second at the eye. For instance, the angular size of the moon is about 31 arcminutes.

$M_\odot$: standing for the mass of our sun, which is 2×10^{30} kg, is a unit that astrophysicists tend to use for all objects larger than the sun.



ripples in our spacetime, which are expected to be detected by gravitational wave detectors of the future.

Do black holes die?

Intuitively, it seems as if there is a sense of permanence about a black hole because nothing that it takes in can come out. This intuitive idea corresponded with the prevailing scientific understanding until the mid-70's. In 1974, however, Stephen Hawking worked out a baffling prediction. By combining Einstein's theory of General Relativity and Quantum Theory, he found that a black hole could not be completely black after all. Due to quantum effects, it would radiate and, therefore, lose mass. The lower the mass of the black hole, the more luminous this radiation was predicted to be. This implies that a gradually radiating and diminishing black hole would eventually disappear in a very luminous flash. For the kind of astrophysical black holes that we are familiar with (both the 'small' and the giant ones), this radiation (known as **Hawking radiation**) is so small that it cannot be detected even with state-of-the-art devices. While a recent claim suggests that it may be possible to measure radiations from 'analogue' black holes created in the laboratory, astrophysical Hawking radiation remains an unobserved theoretical prediction as of now.[8]

To conclude

The only giant black holes we know of are found in the hearts of galaxies. These have always been full of surprises. The most spectacular one to come to light in the last decade is that the growth of giant black holes appears to go hand-in-hand with the growth of the galaxies that they inhabit.[9] This may even be true of the giant black hole in the heart of our own galaxy, which is much, much tinier than the MIlky Way. However, in the process of growing and glowing, this black hole may have played an important role in the evolution of our galaxy — including, among a myriad other processes, the birth of our sun and its planetary system. Understanding how and why this happens, and if it does indeed happen, is essential to build a more coherent story of giant black holes. Thus, these questions continue to intrigue astrophysicists today.

Key takeaways

- Black holes are chunks of space that exert such a strong force of gravity that even light cannot escape from them.
- It seems likely that black holes may have originated from seeds formed by the collapse of extremely large clouds of gas in the very early universe.
- We have long suspected the existence of black holes because of powerful beacons of light emitted from their immediate vicinity.
- Today, black holes are detected through elliptical star orbits in the heart of galaxies, or through the ripples they create in spacetime.
- It seems plausible that black holes may eventually disappear because of the gradual loss of mass through radiation.

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Note: Image used in the background of the article title — An artist's conception of a supermassive black hole. Credits: NASA/JPL-Caltech. URL: https://commons.wikimedia.org/wiki/File:Black_Holes_-_Monsters_in_Space.jpg. License: CC-BY.

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