Section 1: Studying the Sky

• How do astronomers study the Universe?

For hundreds of years telescopes have been used to study the night sky. A simple telescope can be made using two lenses to produce a magnified image. However, using lenses has significant disadvantages. Large glass lenses are difficult to make without imperfections and as lenses are made bigger they can deform under their own weight. Also, different wavelengths of light can be affected differently when they pass through the glass so this has to be corrected for, and some wavelengths, like ultraviolet, are blocked completely.

For this reason curved mirrors are normally used instead of lenses. These collect light over a wide area and focus it to produce an image. The advantage of this is that it is far easier to make a large curved mirror than to make a large polished lens with no imperfections. The largest lens used is around 1m; the largest mirrors exceed 8m.

• Suggested Films

- **Telescopes**
- **How Are Mirrors Made?**

Sir Isaac Newton's reflector telescope, which he designed in the 17th century

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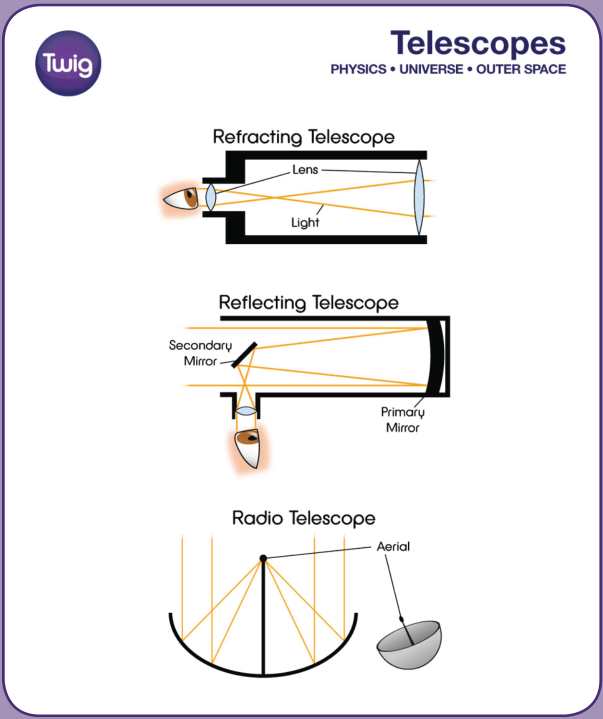

Extension Questions

Q1. Do telescopes only detect visible light?

No. As well as optical telescopes, which detect visible light, there are other types of instrument that can detect ultraviolet, infrared, x-rays, gamma rays and radio waves from distant objects. Some of these wavelengths are blocked by the Earth's atmosphere and so instruments have to be placed into orbit so that they can detect the signals.

Q2. Do astronomers spend their time looking through telescopes?

Astronomers rarely look directly through the eyepiece of their telescopes. Photographic film provides a permanent record of what is being observed and can also be exposed for long periods to pick up faint objects which would be invisible to the human eye.

Modern telescopes record images digitally instead of using photographic film. This is done using light sensitive devices called CCDs (Charge Coupled Devices) to detect light. This is the same technology used in digital cameras.

• How does the Earth's atmosphere affect astronomy?

An effect called atmospheric scintillation causes problems for astronomers. Because the Earth's atmosphere is turbulent the images of stars and other objects appear to move and distort. This is similar to what happens if you look at lights at the bottom of a swimming pool, the movement of the water will disrupt the path of the light and distort the image. This is the reason the stars appear to twinkle.

• Suggested Film

- Hubble Space Telescope
- Kittinger: First Man in Space?

Extension Questions

Q3. Why are telescopes sent into space?

Telescopes could be placed above the atmosphere to avoid the effects of atmospheric scintillation and to detect wavelengths of light which cannot pass through the Earth's atmosphere. Atmospheric scintillation was the reason the Hubble Space Telescope was launched in 1990. Hubble was the first of NASA's four 'great observatories', each looking at a different type of light. Hubble looks at visible light and near ultraviolet. The Compton Gamma Ray Observatory was launched in 1991 and operated until 2000 when one of its gyroscopes failed and it was deliberately crashed into the Pacific Ocean. The Chandra X-Ray Observatory was launched in 1999 followed by the Spitzer Space Telescope, designed to operate in the infrared, in 2003. In 2009, as planned, Spitzer's coolant ran out, although it is still able to take some measurements.

NASA, in conjunction with the European Space Agency (ESA) and the Canadian Space Agency (CSA), plans to launch the James Webb Space Telescope in 2018. It will work in the infrared, which is blocked by the Earth's atmosphere, to look for light from the first stars and galaxies. It will have a 6.5m mirror made of 18 segments.

Q4. How can telescopes on Earth correct for the effects of the atmosphere?

Even if telescopes cannot be launched into space there are ways to reduce the effect of atmospheric scintillation. Observatories are usually constructed at high altitudes where the atmosphere is thinner and the effect of turbulence is reduced. There will still be distortion but there are ways to remove it.

For example, it is possible to remove distortion in the image by changing the shape of the mirror rapidly to compensate. To know exactly how the mirror should be changed the form of the turbulence must be known. This can be done using a nearby star, or an 'artificial star' projected into the upper atmosphere using a laser, and monitoring its distortion. This is then used to calculate the required adjustment to the mirror.

Lucky imaging is used by both professional and amateur astronomers. It involves taking many images very quickly, selecting the images with the least distortion, and combining them while discarding the others. This can be very effective.

Speckle imaging uses image processing. Like lucky imaging it involves taking many pictures over a very short timescale, but instead of choosing only the best images it corrects for the distortion in each image before recombining them.

Extension Questions

Q5. How large are the most powerful telescopes?

Radio telescopes, shaped like giant satellite dishes, can be enormous. The Arecibo telescope in Puerto Rico is around 300m in diameter and China is currently building FAST (Five hundred metre Aperture Spherical Telescope) which will have a diameter of 500m, about the same length as five football pitches.

Also, telescopes which are far apart can be linked together to create the equivalent of a very large telescope. This can be used to help measure the diameters of distant objects.

Optical telescopes, which look at visible light, are made as large as possible to collect as much light as possible and image faint objects. However, manufacturing reflectors bigger than 5m presents problems. It is difficult to make large mirrors with the required precision and the weight of the mirror begins to become a problem, as it begins to sag under its own weight. For this reason larger mirrors are made of segments, and these have to be manufactured very precisely.

The largest telescopes have mirrors around 10m in diameter (the Hubble Space Telescope has a 2.4m diameter mirror). Several are planned which will be much larger. The European Southern Observatory (ESO) had considered a project called OWL (Overwhelming Large Telescope) which would have had a segmented mirror 100m in diameter, but it was decided that the cost at around £1 billion was too high.

Q6. What are liquid mirrors?

One alternative to using segmented mirrors is to use a liquid. If a liquid is rotated its surface becomes curved. To use this effect a liquid metal must be used. Mercury is the most obvious choice, as it is liquid at room temperature, but it is toxic to humans and animals. Gallium is a liquid above 30°C and there are alloys of gallium and indium, which are liquid at room temperature, but these are more expensive. Liquid mirrors are very cheap compared to polished metal mirrors, but have limitations as the telescope cannot be tilted from the vertical or the liquid loses its shape.

Section 2: The Scale of the Universe

• How are astronomical distances expressed?

When considering distances between stars or galaxies it is not useful to use units like kilometres, as the distances are too large. Kilometres could perhaps be used for distances within the Solar System. The Moon is about 384,000km from the Earth, and the Sun is about 150,000,000km from the Earth. However, the nearest star is around 40,000,000,000,000km from the Sun. The distance to the nearest spiral galaxy, Andromeda, is 20,000,000,000,000,000,000km. We obviously need to use different units. There are three units which are commonly used to measure distances in astronomy: light years, parsecs and astronomical units (AU).

• Suggested Films

- Scale of the Universe

- What Is a Light Year?

Extension Questions

Q7. What is a light year?

Light travels extremely quickly. In one second light travels 300,000km, approximately the distance from Earth to the Moon. We could define this as one light second. Similarly, the distance light travels in one year is about 9,500,000,000,000km and we define this as a light year. When these units are used we find that the distance from the Earth to the Sun is around 8.3 light minutes, and the distance to the nearest star, Proxima Centauri, is 4.2 light years. Andromeda is approximately 2.5 million light years away, and the edge of the observable Universe is about 46 billion light years away. Our most distant spacecraft, Voyager 1, is around 25 light hours away.

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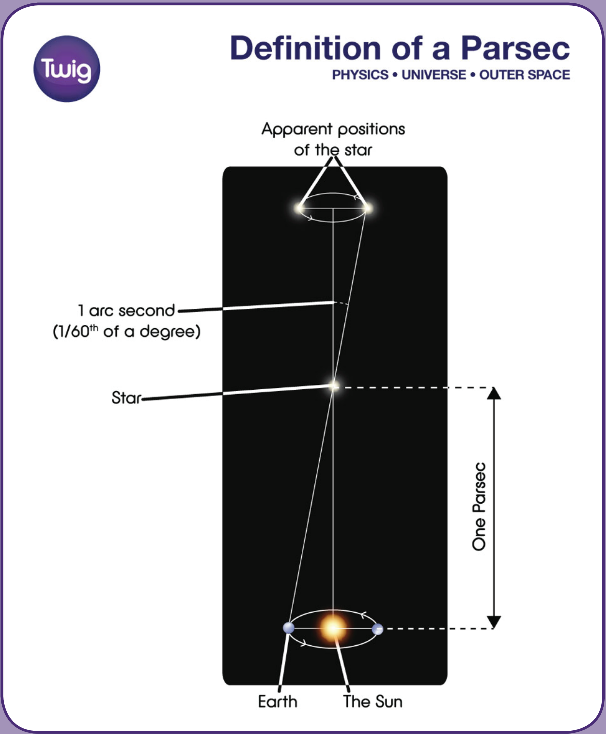


Q8. What is a parsec?

Parsecs are also used to measure large distances. Because the Earth orbits the Sun, if a star's position can be noted six months apart it will appear to have moved in the sky. This effect is called parallax. The same effect can be observed by holding a finger in front of your face and viewing it through one eye, then the other. Stars are very far away and so the effect is small. Astronomers look at the angle that a star appears to have shifted, and if a star appears to shift by a sixtieth of a degree we say it is at a distance of 1 parsec. This is equivalent to around 3.26 light years.

The nearest star, Proxima Centauri, is over 4 light years away. This means that all known stars are at a distance greater than one parsec, and the further the star the smaller the apparent shift in its position. This means that this method is difficult to use for large distances, especially as the Earth's atmosphere limits our ability to obtain sharp images of stars.

The ESA Hipparcos (High Precision Parallax Collecting Satellite) mission, launched in 1989, measured stars up to 1000 parsecs away.

NASA had planned a similar mission, FAME (Full-sky Astrometric Mapping Explorer), but this was cancelled in 2002, two years before it was planned to launch.

The ESA will launch a successor to Hipparcos, Gaia, which will be 10 times more accurate. Its accuracy of 0.00001 arcseconds will allow it to catalogue around 1 billion stars up to a distance of around 8000 parsecs.

Q9. What is an astronomical unit?

The astronomical unit (AU) is derived from the radius of the Earth's orbit around the Sun. It is often used as it helps defines the parsec, which is related to the diameter of the Earth's orbit around the Sun. The AU is useful when dealing with distances within the Solar System. Mars is approximately 1.5 AU from the Sun and the furthest planet from the Sun, Neptune, orbits at around 30 AU from the Sun, or approximately 4 light hours. The limit of the solar wind from the Sun is at around 100 AU. The most distant boundary of the Solar System, the edge of the Oort Cloud, a region of frozen objects which is thought to exist far beyond the outer planets, may be as far as 100,000 AU or 1.6 light years.

• How are distances measured in astronomy?

In astronomy it is important to know the scale of the Universe and the distance to stars, galaxies and other objects. It is not possible to travel to these objects to measure the distance between them and Earth, therefore astronomers have to use other, ingenious ways of calculating distances.

Using parallax, the apparent change in the position of a star when the Earth is in two different positions, only works for relatively short distances. It is hoped that this method will soon be extended to measure the distances to stars thousands of parsecs away, but this would still be less than a third of the diameter of our own Galaxy.

Standard candles are often used. These are objects of a particular class where we know their properties and we can predict their brightness. We then compare that with the brightness we observe and, as we know that the farther the object the dimmer the light from it will be, we can predict how far away the object is. There are complications, however, for example, light may have been absorbed by dust or gas between the object and the Earth, and if this is not accounted for properly it may seem that the object if farther away than it actually is.

The Hubble Space Telescope

• Suggested Films

- **Scale of the Universe**
- **What Is a Light Year?**
- **FactPack: Redshift**

As the Universe is expanding we are able to determine that the farther away an object is the faster it will be travelling away from us. If we know the form of this relationship (given by the Hubble constant – thought to be approximately 70 kilometres per second for every million parsecs) we would be able to determine the distance of an object if we knew the speed it appeared to be travelling away from us. The speed can be determined through something known as redshift. The faster an object is travelling away from us the more the frequency of light it is emitting seems to be shifted to the red end of the spectrum. As we know the frequencies of light usually emitted by different types of stars we can calculate the size of this shift, calculate the apparent speed and use the Hubble constant to find the likely distance.

Extension Questions

Q10. What are Cepheid variable stars?

Cepheid variable stars are stars which expand and contract in a predictable way. It is thought that the stars contain helium and, as they heat, the helium becomes doubly ionised (loses two electrons) and then absorbs heat. This makes the star expand and the outer layers cool. They then switch to being singly ionised and in this form the heat passes through them and escapes. Because of this the star cools down, the outer layers fall back towards the centre, they are heated and become doubly ionised again, and the process repeats.

The brightness of the star is related to the period of its expansion and contraction. This means that measuring the time taken for the star to cycle lets us calculate its brightness. This means the star can be used as a standard candle and used to calculate distance.

Q11. What else can be used as a standard candle?

A particular type of supernova, a type 1a supernova, occurs when a white dwarf star of a particular size explodes. This occurs when a white dwarf star gradually collects material from a neighbour, reaches the required size and detonates. Because this only happens for a particular size the brightness of the explosion is thought to always be the same. For this reason type 1a supernova can be used as standard candles to calculate distances.

• How large is the Universe?

As it takes time for the light from stars to reach us, there are areas of the Universe we cannot observe, as the light from these areas has not had time to get to us since the Universe was created. We believe that the Big Bang occurred 13.8 billion years ago, so we might expect that the edge of the observable Universe is 13.8 billion light years away in every direction. In fact, the Universe has been expanding since the Big Bang, and although the light from the edge of the observable Universe has been travelling for 13.8 billion years, the edge is now thought to be 46.5 billion light years away (14 billion parsecs).

Extension Questions

• Suggested Film

- Scale of the Universe

Q12. What is the most distant object that has ever been observed?

Gamma ray bursts are the most luminous events in the Universe. They are thought to occur when a very large star collapses, becoming a black hole and causing an explosion that is sometimes referred to as a hypernova. A gamma ray burst is caused when material from the outer regions of the star falls into the black hole. If the black hole is rotating at high speed, this leads to jets of material being expelled at close to the speed of light along the rotational axis of the black hole. If these jets are pointed towards Earth a gamma ray burst is observed.

In 2004, NASA's SWIFT spacecraft was launched to detect and observe gamma ray bursts. As gamma ray bursts are short-lived, SWIFT is designed to scan the sky until a burst is detected, then rotate to point at the event. When the event has been located, other telescopes can then be alerted to observe it. SWIFT has now observed more than 500 gamma ray bursts.

In 2009, SWIFT observed the gamma ray burst GRB 090423; it is the most distant object ever observed. The light from GRB 090423 was emitted over 13 billion years ago, only 630 million years after the Big Bang. This could mean that the star involved is one of the first generation of stars which formed after the Universe came into existence.

Section 3: The Universe

• What is the Universe made of?

The Universe contains billions of galaxies, each containing billions of stars. The galaxies are tens of thousands of light years across and are separated by distances of a few million light years. The Universe is around 13.8 billion years old and, due to expansion, the visible Universe stretches around 45 billion light years in all directions from us.

The Universe has been expanding since the Big Bang, and the galaxies appear to be travelling away from each other for this reason. As time passes we might expect the gravitational attraction of the galaxies to slow down the expansion and, perhaps, even stop it and begin to pull the galaxies back together again; finally ending in a "Big Crunch", perhaps followed by another Big Bang. Alternatively, we could imagine that the gravitational attraction due to all the matter in the Universe may not be strong enough to stop the expansion, and the Universe would continue expanding forever. The galaxies would travel further and further apart until, after an unimaginable length of time, the material available for stars was finally exhausted. After the last stars stopped shining the remnants would slowly decay until, eventually, the Universe became the same temperature. This is known as heat death.

However, there are some complications. In 1934, an astronomer called Fritz Zwicky found a problem with the velocity of some galaxies. He pointed out that the mass which was visible, was not enough to account for how fast they were moving.

Forty years later, Vera Rubin measured the way stars move within galaxies. It was expected that the greater the distance a star is from the centre of a galaxy, the more slowly it will be travelling. Instead, the results showed very little difference in the velocities of the stars. It seems that there is something we cannot yet detect that is exerting a gravitational attraction on these stars. This has been given the name dark matter and it is still not clear exactly what it is.

Another problem emerged after measurements in the late 1990s. Measurements of supernova showed that instead the expansion of the Universe slowing since the Big Bang, as had always been assumed, the expansion is actually accelerating. Something is pushing the galaxies further away from each other. This is known as dark energy and there is no generally agreed explanation for this effect.

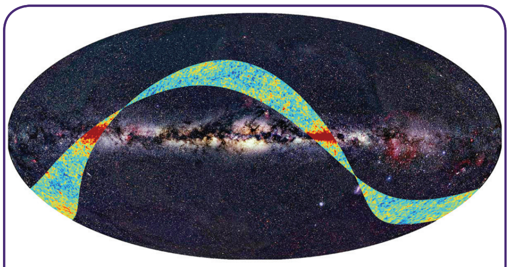
It appears that the majority of the Universe is composed of dark matter and dark energy, whatever they are. All of the mass in the Universe that we can see, such as stars, planets, interstellar gas and galaxies, only accounts for around 4% of the Universe. Around 23% is dark matter and about 73% is dark energy.

Extension Questions

Q13. What is dark matter?

Nobody knows for sure exactly what dark matter is. There are several suggestions.

It is possible that the Universe contains large numbers of dark objects, such as black holes or "stars", which never accumulated enough mass to ignite (brown dwarfs). These MACHOs (Massive Astrophysical Compact Halo Objects) could account for a small amount of dark matter, but for a large proportion of dark matter to be made of these objects, would contradict measurements predicting the amount of matter created in the Big Bang.



An image released by the European Space Agency, which shows the sky mapped by the satellite Planck

• Suggested Films

- The Search For Dark Matter

Another suggestion is that there may be a large number of slowly moving particles, which have relatively large masses but do not interact strongly with ordinary matter. Several efforts are currently underway to detect these WIMPs (Weakly Interacting Massive Particles). These use various methods, but all involve looking for rare collision events between WIMPs and the atoms in the detection apparatus.

Other theories suggest fast moving particles, for example, unknown types of neutrinos. However, these alone do not seem sufficient to explain the properties of dark matter.

Some scientists even suggest that our need for dark matter to explain some observations may mean that some of our physical laws are wrong or incomplete. If the laws of gravity were modified then the unexplained effect, and the need for dark matter would disappear. Whatever the composition of dark matter really is, for now it remains a mystery.

Q14. What is dark energy?

Although scientists know that dark energy exists, because of the accelerating expansion of the Universe, its nature is a complete mystery. We have no real explanation for what 70% of the Universe is made of. As with dark matter, there are several theories.

It is possible that space itself contains energy and, as more space is created as the Universe expands, it is this energy that pushes the Universe to expand more quickly.

Alternatively, there may be some kind of field that exists everywhere in the Universe, perhaps with different strengths at different points, which causes this acceleration. This theory is known as quintessence.

Like dark matter, some scientists believe dark energy is a sign that something is wrong with our theories of gravity, and have attempted to modify the predicted behaviour of gravity at large scales to remove the need for dark energy. However, no convincing alternative theory has yet been found.

NASA is currently planning a project called WFIRST (Wide Field Infra Red Survey Telescope) which will launch in about 2020. It will search for evidence of dark energy and aim to help decide exactly what dark energy is.

• What are galaxies?

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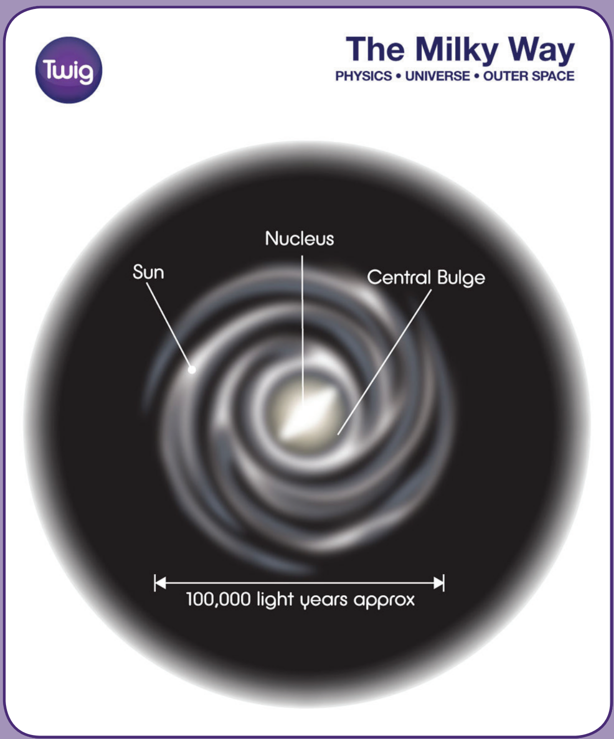


A galaxy is a large structure containing billions of stars. The Sun and the Earth lie about 25,000 light years from the centre of the Milky Way galaxy. On a clear night the Milky Way forms a band of light across the sky. However, this is difficult to observe from urban areas where it is obscured by light pollution caused by artificial light being scattered into the sky.

The Milky Way is a barred spiral galaxy where the Solar System is located. It contains hundreds of billions of stars. It is approximately 100,000 light years across and around 1000 light years thick, bugling at the centre. Until the 1920s, when Edwin Hubble was able to show that some stars lay outside the Milky Way, it was believed that the Milky Way was the entire Universe.

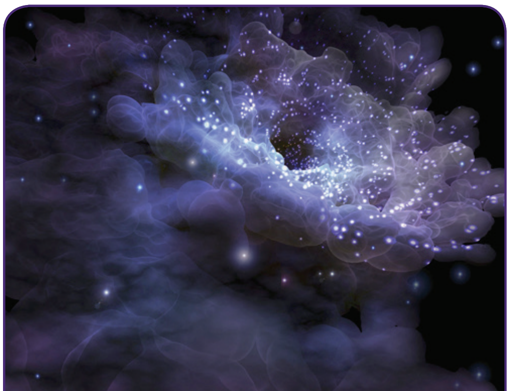
The Milky Way is part of the Local Group of galaxies. The Local Group has a diameter of around 10 million light years and includes around 30 galaxies, including Andromeda and several galaxies which orbit the Milky Way. It is part of the Virgo Supercluster which contains around 100 galaxy clusters like the Local Group.

The entire observable Universe is thought to contain 80 billion galaxies and an estimated 50 sextillion stars (this is 5 followed by 22 zeroes).

• What is at the centre of galaxies?

It is thought that almost every galaxy has a supermassive black hole at its centre. The centre of our own galaxy is difficult to observe because of interstellar dust which obscures our view. However, gamma rays, X-rays, infrared and radio waves can pass through the dust and so the galactic centre can be observed at these wavelengths.

Astronomers believe that the centre of the Milky Way contains a black hole over 4 million times the mass of the Sun. In 2008 the boundary of this black hole, the event horizon, was measured and found to be 44 million kilometres, about one third of Earth's distance from the Sun.



An artist's rendition of a black hole

• Suggested Films

- **Black Holes**
- **Milky Way's Black Hole**

Extension Questions

Q15. What shape are galaxies?

Galaxies have a range of shapes. Elliptical galaxies range in shape from spherical to almost disc-like. Spiral galaxies are disc shaped with a central bulge and, usually, two spiral arms (although the Milky Way has four). They also have a relatively sparse spherical halo of stars. In addition to these shapes, some galaxies have irregular shapes such as rings, due to collisions.

Extension Questions

Q16. What is a quasar?

In the 1950s a number of very bright, very distant objects were found. There was no obvious explanation for these quasars (Quasi Stellar Radio Sources), as they appeared too bright to be caused by any known mechanism.

It is now known that quasars are galaxies with large, supermassive black holes at their centre. As material spirals into the black hole, enormous amounts of energy are released. When the black hole has consumed the dust and gas near it, the brightness decreases. For this reason quasars only occur with young galaxies.

Q17. What is a black hole?

If a star goes supernova and the mass of the star is very large, it is thought that the core of the star can collapse to become a black hole. The gravitational pull of a black hole is so great that even light cannot escape from it. The centre of a black hole is known as the singularity, a point with no volume and hence infinite density. The border of a black hole is called the event horizon; anything within the event horizon cannot escape from the black hole.

Most scientists agree that black holes exist. They have not been directly observed, but effects have been observed which are consistent with predictions of black hole behaviour.

Q18. What eventually happens to black holes?

Black holes are predicted to emit Hawking radiation, named after the physicist Stephen Hawking. This seems impossible, as nothing, including light, can escape from the event horizon of the black hole.

There is one mechanism which could result in a black hole emitting radiation. Virtual particles can come into existence for a short time before disappearing again. Normally, if a pair of virtual particles are created, these would quickly recombine and disappear, but if they are created near the event horizon of the black hole it is possible that one would fall towards the centre of the black hole while the other escapes. This would result in radiation being emitted from the black hole.

The more massive the black hole, the less radiation will be emitted. This means black holes which have a large mass emit less radiation and take longer to “evaporate”. It would take an enormous length of time for a black hole to disappear through this process. It is thought that a black hole with the same mass as our Sun would take many, many times the current age of the Universe to evaporate.

Smaller black holes should evaporate more quickly, perhaps over a few billion years. As the black holes emit more radiation they will become smaller, causing them to emit more radiation. This could eventually lead to a large explosion. Some astronomers are currently searching for evidence of explosions from these black holes. One of the missions of NASA’s Fermi Gamma Ray Space Telescope, which launched in 2008 and currently orbiting the Earth, is to search for evidence of these events.

Some scientists have suggested that micro black holes could be created in the Large Hadron Collider. However, this is generally thought to be unlikely. If micro black holes were created they would evaporate almost instantly.

Q19. Who first predicted the existence of black holes?

The idea of a dark star with a mass and gravitational pull so large that light would not be able to leave its surface, was first predicted by John Michell in 1783, and Pierre-Simon Laplace in 1796, although these ideas were not compatible with the idea that light was a wave without mass, which was not influenced by gravity.

In 1915, Einstein’s theory of general relativity showed that gravity affected light and it was shown that black holes were theoretically possible. However, many scientists, including Einstein, believed black holes could not exist, and it was only in the 1960s that it began to be generally accepted that black holes were real objects.

• Quizzes

Black Holes

Basic

• What is the accretion disc of a black hole?

A – the boundary of the area that light cannot escape from

B – the area at the centre of the black hole

C – an area of hot gas falling into the black hole

• What is the event horizon of a black hole?

A – the boundary of the area that light cannot escape from

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• What is the singularity of a black hole?

A – the boundary of the area that light cannot escape from

B – the area at the centre of the black hole

C – an area of hot gas falling into the black hole

• How large is the area at the centre of a black hole?

A – a single point

B – 4 times as large as our Sun

C – a few km across

Advanced

• How massive must a star be for its collapse to lead to a black hole?

A – at least 4 times as massive as our Sun

B – at least 20 times as massive as our Sun

C – at least 100 times as massive as our Sun

• What happens in a supernova explosion?

A – the star is dragging in material from its surroundings

B – the star is burning all of its fuel at once

C – the outward layers of the star are blown outwards

• Which of the following describes what is it like at the centre of the black hole?

A – the gravitational pull is enormous

B – nuclear reactions are taking place

C – matter is being thrown out at high speed

• How can material be thrown from around the black hole?

A – if the material is very hot

B – if the black hole is spinning rapidly

C – if the black hole has run out of fuel

Scale of the Universe

Basic

- Approximately how wide is the planet Earth?

  A – 6300 km

  B – 12,800 km

  C – 34,000 km

- How wide is the Solar System?

  A – 1,000,000 km

  B – 1.6 light years

  C – 100,000 light years

- How large is the Universe?

  A – 120 million light years across

  B – billions of light years across

  C – billions of light years across and still expanding

Advanced

- What is the distance across the Milky Way?

  A – 100,000 light years

  B – 5 million light years

  C – 120 million light years

- What is the distance across the Local Group?

  A – 100,000 light years

  B – 5 million light years

  C – 120 million light years

- What is the distance across the Local Supercluster?

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  B – 120 million light years

  C – billions of light years

• Answers

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