Gamma ray astronomy - the 40 year challenge

Invisible cosmology

by Philip Corneille

Gamma rays have been studied by several series of unmanned spacecraft since the 1960s. Four decades later, astronomers are finally starting to understand these high-energy detections, which are linked to extremely violent phenomena in space such as supernovae and black holes. *Philip Corneille* continues his series on space astronomy and finds out there is more to the universe than meets the eye.

Gamma ray bursts

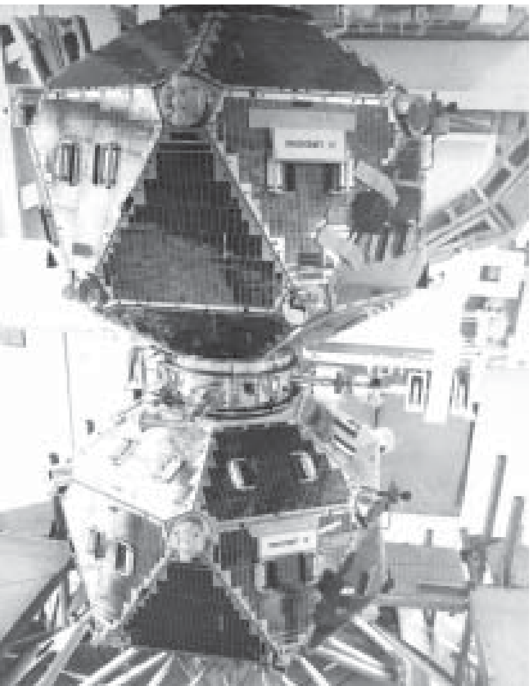
At the beginning of the 20th century, French chemist Paul Ulrich Villard discovered gamma rays while working with Uranium. British physicists William Henry Bragg (1910) and Ernest Rutherford (1914) studied these rays. In fact, gamma rays are electromagnetic radiation with the highest energy and frequency produced from sub-atomic particle interaction, such as radioactive decay and nuclear reactions in outer space.

Earth's atmosphere blocks the harmful gamma rays so to study them effectively astronomers need detectors in space.

The first gamma ray telescope carried into orbit on the Explorer XI spacecraft in 1961 detected the first cosmic gamma ray photons.

However, the most spectacular gamma rays detections were made by military satellites. Project 'Vela' started in 1959 and was developed by the American Advanced Research Projects Agency (ARPA) in order to implement methods to monitor compliance with the 1963 partial test ban treaty on nuclear weapons.

Pair of 1967 US military Vela spacecraft in clean room before launch. These reconnaissance satellites were the first ever to detect Gamma Ray Bursts. USAF/Dwayne Day



It consisted of three elements - Vela 'Uniform' to monitor seismic signals to detect underground nuclear testing, Vela 'Sierra' to detect atmospheric nuclear tests and Vela 'Hotel' to detect nuclear testing from space. The latter element consisted of a group of reconnaissance satellites operated by the US Air Force.

A total of 12 spacecraft were built by Thompson-Ramo-Wooldridge (TRW) in two series - six of the Vela Hotel design and six of the advanced Vela design. The original Vela series were equipped with 12 external X-ray detectors and 18 internal gamma ray and neutron detectors.

The advanced Vela spacecraft series had additional non-imaging silicon photodiodes and sensors which could detect the electromagnetic pulse of an atmospheric nuclear test. These reconnaissance satellites were launched in pairs by Atlas-Agena (Vela 1963-1965) or Titan III (advanced Vela 1967-1970) military launch vehicles and placed in 100000 kilometre High Earth Orbits (HEO).

The Vela vehicles detected gamma rays coming from random directions in outer space but this discovery wasn't declassified until 1973. These satellites had detected the most energetic events in the universe, known as Gamma Ray Bursts (GRB).

Although the spacecraft had a design lifetime of six months, satellite 9 operated for nearly 15 years.

Gamma ray telescopes

The discovery of GRBs was confirmed by later space missions, including Apollo and the Soviet Venera probes to Venus. Pioneering gamma ray detecting satellites included the Small Astronomy Satellite (SAS II - 1972), which carried a spark chamber gamma ray telescope, the European COS B (ESA - 1975), which operated for six years, and the High Energy Astronomy Observatories (HEAO 1 to 3 - 1977).

ESA's 1975 Cos-B spacecraft provided the first complete galactic survey in high-energy gamma rays. Before this, the gamma-ray Universe had largely been invisible to astronomers. ESA

HEAO 3, launched by NASA in 1979, was a dedicated x-ray and gamma ray survey mission, which surveyed the entire sky. However, due to the low resolution, it remained impossible to identify point gamma ray sources with individual stars or stellar systems. Theorists started to speculate whether GRBs came from within our galaxy or had an extragalactic origin.

In the late 1990s, the cooperation between NASA's great observatories, the

NASA’s 2004 Swift satellite’s three telescopes work together to quickly pinpoint gamma-ray bursts and make multi-wavelength observations of the afterglows. ***NASA/GSFC***

Artist impression of ESA’s 2002 Integral fine spectroscopy spacecraft shown examining the energetic gamma ray jets of a hypernova. *ESA*

Hubble Space Telescope (HST – launched from Space Shuttle Discovery during STS-31 in April 1990) and the Compton Gamma Ray Observatory (CGRO - launched from shuttle Atlantis during STS-37 in April 1991), brought major advancements in gamma ray astronomy as their instruments realised an improvement in sensitivity by a factor of ten over previous missions.

Moreover, scientists got results from two additional spacecraft - the RXTE (Rossi X-ray Timing Explorer – December 1995) and the Italian-Dutch BeppoSAX (Satellite per Astronomia X – April 1996).

The latter spacecraft successfully detected the longer wavelength afterglow of GRB 970508 (8 May 1997), which allowed a redshift measurement (distance) confirming that the GRB was extragalactic.

In January 1999, GRB 990123 was the first GRB for which optical emission was detected before the gamma rays had ceased. It was examined by ground-based telescopes in combination with observations by BeppoSAX and CGRO. At the location of GRB 990123, the HST picked up traces of a faint distant galaxy, whose blue colour suggested it was forming new stars at a high rate.

Finally though, after 30 years of Gamma ray astronomy, scientific results ruled out the galactic origin of GRBs. It appeared that GRBs seemed to exist in two distinct categories, short duration hard-spectrum, and long duration soft-spectrum bursts, suggesting two different classes of gamma ray sources.

Origin of GRBs

After the forced de-orbit of CGRO due to a gyroscope failure in June 2000, an era of intense international collaboration started as the scientific community got two new spacecraft - High Energy Transient Explorer-2 (HETE-2 - October 2000) and the International Gamma-ray Astrophysics Laboratory (Integral - October 2002).

HETE-2 is a small scientific satellite designed to detect and localise GRBs. The coordinates of detected GRBs are distributed to ground-based telescopes within seconds of burst detection, thereby allowing detailed observations of the initial phases of a GRB.

Europe’s Integral spacecraft is the first space observatory that can simultaneously observe objects in gamma rays, X-rays and visible light. The impressive four tonne Integral circles the Earth in a heliocentric orbit at 60,000 kilometres, well outside the Van Allen radiation belts to avoid interferences.

After the controlled de-orbit of BeppoSAX (April 2003), astronomers got a new spacecraft with improved instruments, Swift (November 2004), a NASA mission with British and Italian cooperation.

Swift has multi-wavelength observation capability (Gamma + X-ray + Ultraviolet + visible) in order to examine a GRB immediately after detection.

Cooperation with both space-based telescopes and ground-based observatories remains invaluable. Large aperture telescopes, such as the Very Large Telescope of the European Southern Observatory (ESO) in Chile and the Keck telescopes in Hawaii, can examine the GRB afterglow in order to measure the cosmological distance of the GRB source.

After six months of operations, Swift detected the flash of two neutron stars crashing together. Swift’s examination of the afterglow marked the first identification of the location of a short-duration hard spectrum GRB. Other observations proved that GRBs and supernovae (explosions linked to the death of massive stars) are linked.

In July 2005, Astro E-2, a powerful orbiting US-Japanese observatory dedicated to high energy measurements in galaxies, neutron stars and the environments around black holes, joined the armada of space telescopes. It carries a hard X-ray detector for broadband spectroscopy up to the gamma ray region.

GRB host studies

In September 2005, Swift detected GRB 050904 with a redshift value of 6.3 and a duration of 200 seconds. At 12.6 billion light years, it was the most distant GRB ever detected.

This meant that the GRB occurred in the early universe as the flash had travelled for more than three-quarters the age of the universe.

The confirmed immense distance scale of long duration GRBs allows astronomers to look back into time to the cosmic dark age. The distance scale also imposes immense demands on the energetics of the GRB explosion.

No known processes in outer space are able to quickly liberate immense energy, so long GRB emission is believed to be released in narrow jets, not spherical shells. In contrast, less luminous short GRBs are less beamed and intrinsically less energetic.

Since October 2006, astronomers have been able to use the GRB Host Studies database (www.grbhosts.org) to do their research on the largest known energy bursts since the Big Bang.

The most striking difference between long and short GRBs is in the properties of their host galaxies. Long GRB hosts are mostly blue and star forming and the GRBs occur in their brightest regions. Short GRB hosts are mostly red, old and non-star forming with the GRBs originating away from the host core.

Nowadays, astrophysicists associate long GRBs with the deaths of massive stars, which evolve and die within a few hundred million years in star forming regions. Dr Stan Woosley's 'hypernova' theory explains the collapse of these massive stars into a black hole out of which burst the gamma ray jets. In contrast, no supernovae have been associated with short GRBs and scientists believe these events occur due to the collision of two compact objects such as neutron stars or a neutron star and a black hole. Theorists still study this exception of degenerating binaries.

The future of gamma ray astronomy fully depends on space-based telescopes. The latest is the Astrorivelatore Gamma Immagini LEggero (AGILE – April 2007), an Italian gamma ray astronomical satellite of the next generation.

Next year, in 2008, NASA will launch the Gamma-ray Large Area Space Telescope (GLAST) to further resolve the gamma ray sky in order to determine the spectacular behaviour of some of the most extraordinary objects in our universe.

Space and the evolving universe

by David R Parkinson & Bob Parkinson

We now know that the Universe is 13 billion years old, starting as an incredible fireball and expanding and cooling ever since. We know that, as it cooled, galaxies and stars condensed out of the primordial plasma, and that most of the elements making up our world and our bodies were cooked up in first generation supernovae more than five billion years ago.

We also have become aware that everything that we can see – stars, nebulae, gas and dust – are only a fraction of the total mass in the Universe. There is something that we have called 'dark matter' that out-weighs ordinary matter by a factor of perhaps five to one.

Finally, we have lately discovered that there is something else, something sometimes called 'dark energy', which is causing the expansion of the Universe to accelerate with time.

This is not theory. Each of these results is the result of observation. But what is often unappreciated is that this picture of the Universe comes from space-borne instruments and telescopes. We had to go into Space to discover what our Universe was really like.

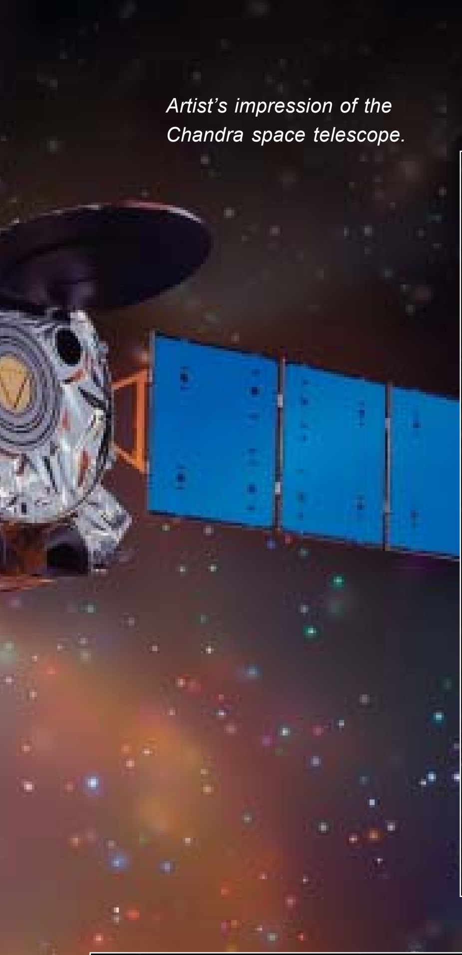
Modern cosmology theory depends on three observable quantities – the curvature of Space, the long-term acceleration of the expanding Universe, and the matter density (and its distribution) throughout Space. Each of these is best measured by a particular part of the electromagnetic spectrum. Unfortunately, the Earth's atmosphere is opaque to most frequencies – 'windows' in the visible spectrum and in radio frequencies being the exceptions. Instead we had to launch our instruments into orbit to measure the properties of the invisible Universe.

Curvature of space

The first direct evidence of the 'Big Bang' origin of the Universe was discovered by Arno Penzias and Robert Wilson in 1964 while testing a very sensitive radio antenna. The discovery was made on the ground, but the antenna and receiver were intended to be used for satellite communications, so that even here there is a Space connection.

They found that wherever in the sky they pointed their antenna towards, there was a faint background noise that they could not eliminate from their receiver. Astronomer Robert Dicke recognised that their noise was in fact the echoes of the primordial fireball, redshifted by a factor of about 1000.

Penzias and Wilson could only make their measurements at one point in the (radio) spectrum. It was not until 1989 that NASA launched the Cosmic Microwave Explorer



Artist's impression of the Chandra space telescope.

ESA's XMM-Newton X-ray telescope used over 170 wafer-thin cylindrical mirrors spread over three telescopes. ESA

WMAP used the Moon to gain velocity for a slingshot to the L2 Lagrange point, one million miles (1.5 million km) beyond the Earth.

Artist's concept of the COBE satellite, predecessor to WMAP, in Earth orbit.

(COBE), capable of making measurements over a spread of frequencies, that it was possible to prove that the Universe has a background temperature of about 3 K, as remnant of its origins.

COBE also found that the background temperature is not quite uniform. Instead it shows slight fluctuations from place to place of about one part in 100,000. These fluctuations are due to slight ripples in the plasma from which the background radiation broke free when the Universe was about 100,000 years old.

Sound waves travelling through the ionised gas that formed the Universe up to that point kept the plasma well mixed, and the ripples relate to the fundamental tones of the Universe at that time. (And yes – the 'Big Bang' does have an acoustic element to it!)

In 2001, the Wilkinson Microwave Anisotropy Probe (WMAP) was launched to make more accurate measurements of these ripples. It was named in honour of David Wilkinson, an experimental physicist who made many major contributions to COBE and WMAP, and died in 2002, shortly after the satellite had been launched. The wavelength of these oscillations acts as a 'standard ruler' – an object whose size is known no matter how far away it is seen. This property can then be used to determine the geometry of the Universe.

The speed of sound of the acoustic waves was about half the speed of light at early times, dropping to zero when the Universe recombined, becoming neutral and transparent. This means there existed a 'sound horizon', the maximum distance that an acoustic wave could travel before recombination.

The size of the sound horizon can easily be computed using simple physics, and readily measured by examining the pattern of oscillations in the temperature fluctuations of the Cosmic Microwave Background (CMB). By comparing the predicted and observed values of this distance we can tell whether light rays from the CMB are converging (elliptical universe), diverging (hyperbolic universe) or parallel (flat universe).

It turns out that the Universe is essentially 'flat' – or Euclidean. That means that if you double the size of a cubical volume of Space, the volume increases by a factor of precisely eight. While this may seem to be obvious it does not have to be so. Since Einstein's theory says that matter distorts space (and space tells matter where to go), the result tells us something of how much mass there is in the Universe.

The CMB does not just give information about the curvature of the Universe; it also gives a host of other information about its initial conditions and evolution. The European Planck or (due to be launched in 2008) will provide even more accurate measurements of the CMB than WMAP.

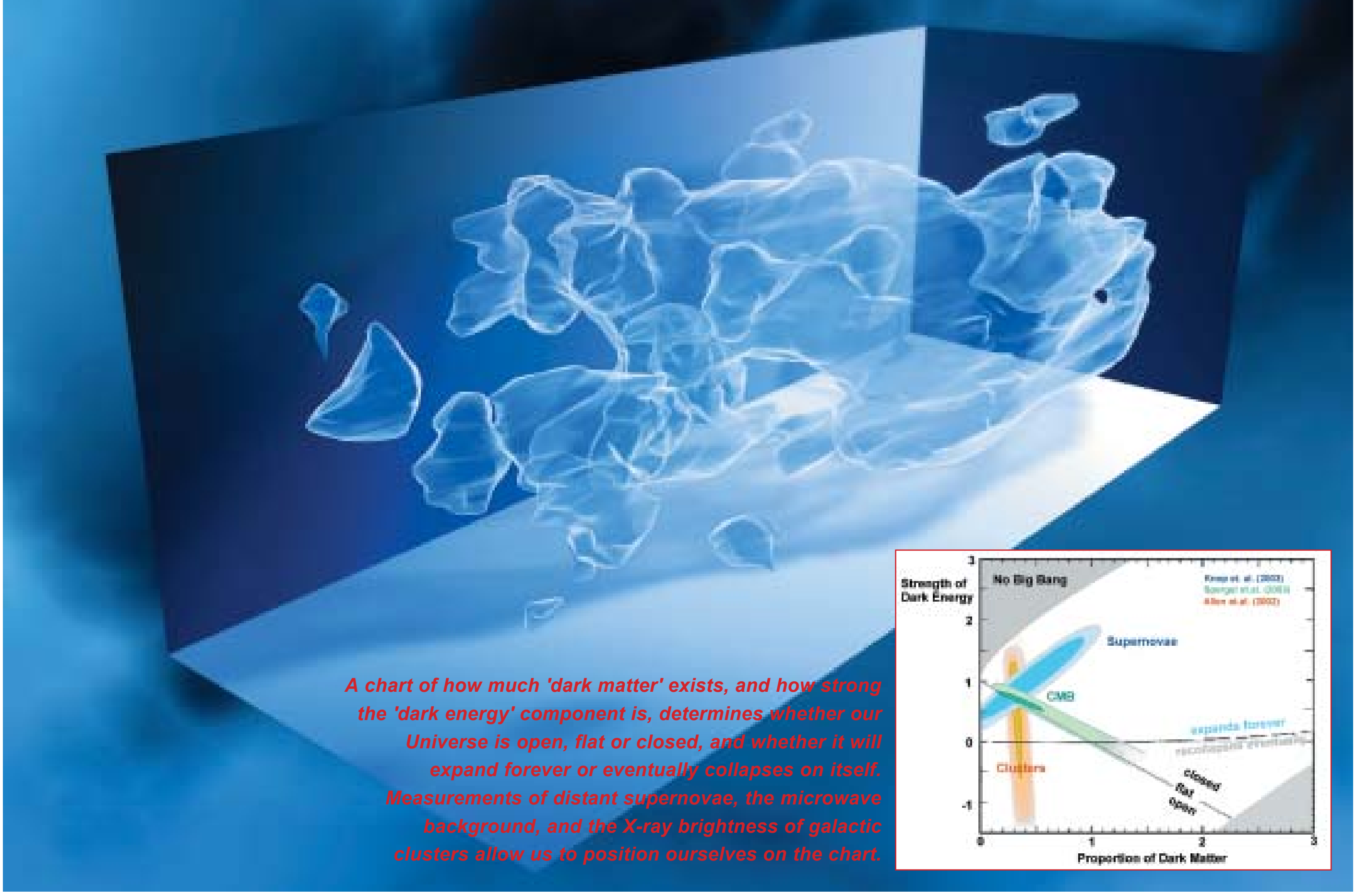
Dark matter

Astronomers first became aware of so-called 'dark matter' when they studied the rotation of spiral galaxies. The velocity of stars at different distances from the centre seemed to indicate that there must be additional, unseen mass in the galaxies, and that it was not concentrated at the centre but distributed over some considerable volume.

The conclusion was that there must be another, invisible source of mass that only interacted with ordinary matter like stars and nebulae through its gravitational field. Various theories were put forward, but the favourite was 'cold, dark matter' in the form of heavy sub-atomic particles that interacted only very weakly with electromagnetism.

The question was, would it ever be possible to 'see' this mysterious substance more directly.

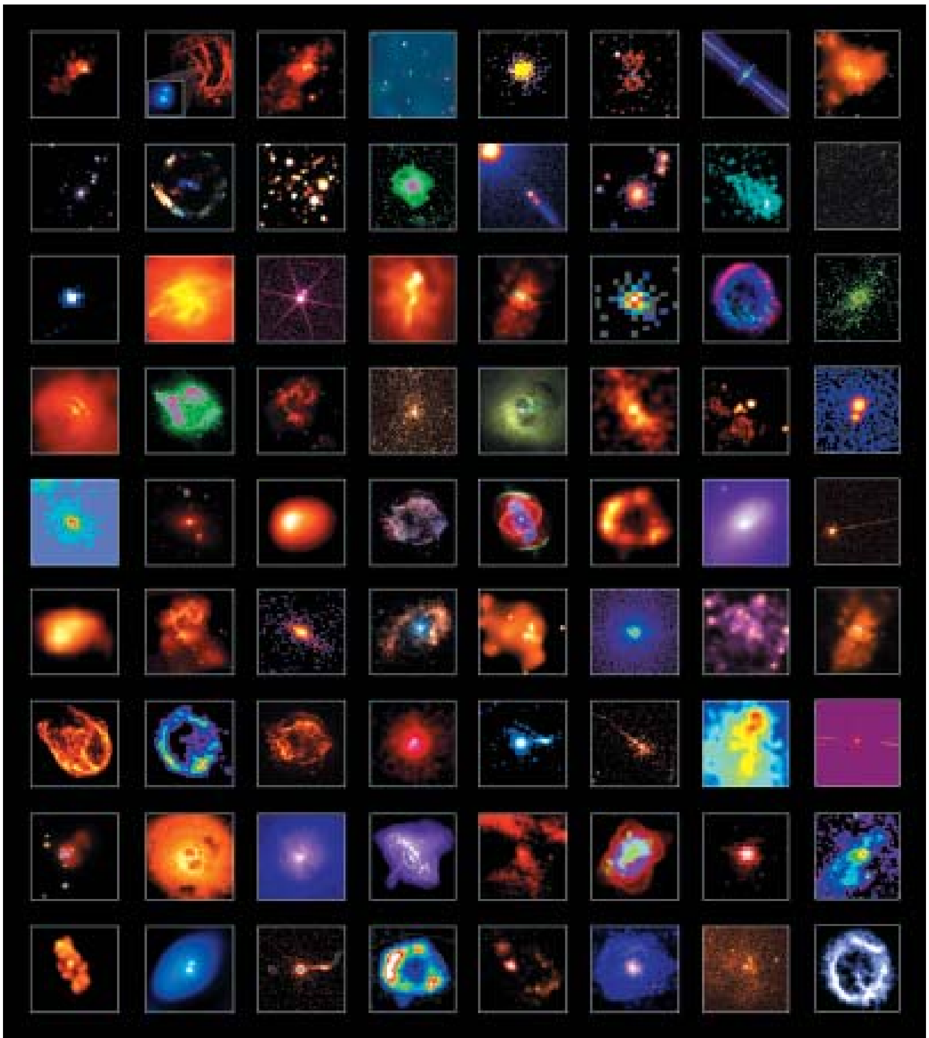
Measuring the amount of matter (both



A chart of how much 'dark matter' exists, and how strong the 'dark energy' component is, determines whether our Universe is open, flat or closed, and whether it will expand forever or eventually collapses on itself. Measurements of distant supernovae, the microwave background, and the X-ray brightness of galactic clusters allow us to position ourselves on the chart.

This three-dimensional map, obtained thanks to HST and XMM-Newton data, offered first look at the web-like large-scale distribution of dark matter, an invisible form of matter that accounts for most of the Universe's mass. The map reveals a loose network of dark matter filaments, gradually collapsing under the relentless pull of gravity, and growing clumpier over time. The three axes of the box correspond to sky position (in right ascension and declination), and distance from the Earth increasing from left to right (as measured by cosmological redshift). Note how the clumping of the dark matter becomes more pronounced, moving right to left across the volume map, from the early Universe to the more recent Universe. ESA/NASA

A collection of 72 images taken by the Chandra X-Ray Observatory within its first two years of operation. NASA/CXC



ordinary and 'dark') in distant objects is always a matter of knowing how much mass there is when we observe some light in the sky. In the case of galactic clusters, the infall of hot gas into the gravitational 'well' of a cluster heats the gas to temperatures of about 10,000 K. At this temperature the 'brightness' of a cluster is found at X-ray wavelengths.

The NASA Chandra X-ray Observatory (July 1999) and the ESA X-ray Multi-Mirror satellite (XMM-Newton – December 1999) measured the x-ray brightness (or luminosity) of distant galactic clusters, and hence to provide an estimate for the amount of unseen 'dark matter' in them.

The result was that there appeared to be about five times as much 'dark matter' in the Universe as ordinary, visible matter. It turns out that most of the Universe we don't see.

More recently, a group of scientists lead by Richard Massey at Caltech used the Hubble Space Telescope to build up a picture of how the dark matter is distributed in Space. It used the principle of gravitational lensing - the deflection of light from distant galaxies by the gravitational attraction of nearby masses. They were not only able to measure the amount of dark matter, but discovered that it was formed into a filamentary structure that 'held-up' the distribution of galaxies.

Acceleration of the Universe

Edwin Hubble, back in the 1920s, first discovered that the Universe was expanding by observing that more distant galaxies had a higher redshift than nearby ones. The change in wavelength (towards the red end of the spectrum) tells us how fast stars and galaxies are moving away from us through the Doppler effect. However, to measure the expansion it is also necessary to know how far away these distant objects are.

Astronomers measure distances far into the Universe through so-called 'standard candles'. For a long time the best 'standard candle' was a type of star known as a Cepheid variable. It was known from measurements of nearby stars that the brightness of a Cepheid variable was related to its period – so that by looking for such stars in other galaxies and measuring how bright they appeared, we could estimate how far away they were.

The problem is that if we want to see distances halfway across the Universe (and halfway back in time), when the galaxies themselves appear only as faint smudges of light, you cannot see individual stars. Instead you need a 'candle' which is much, much brighter – like a supernova.

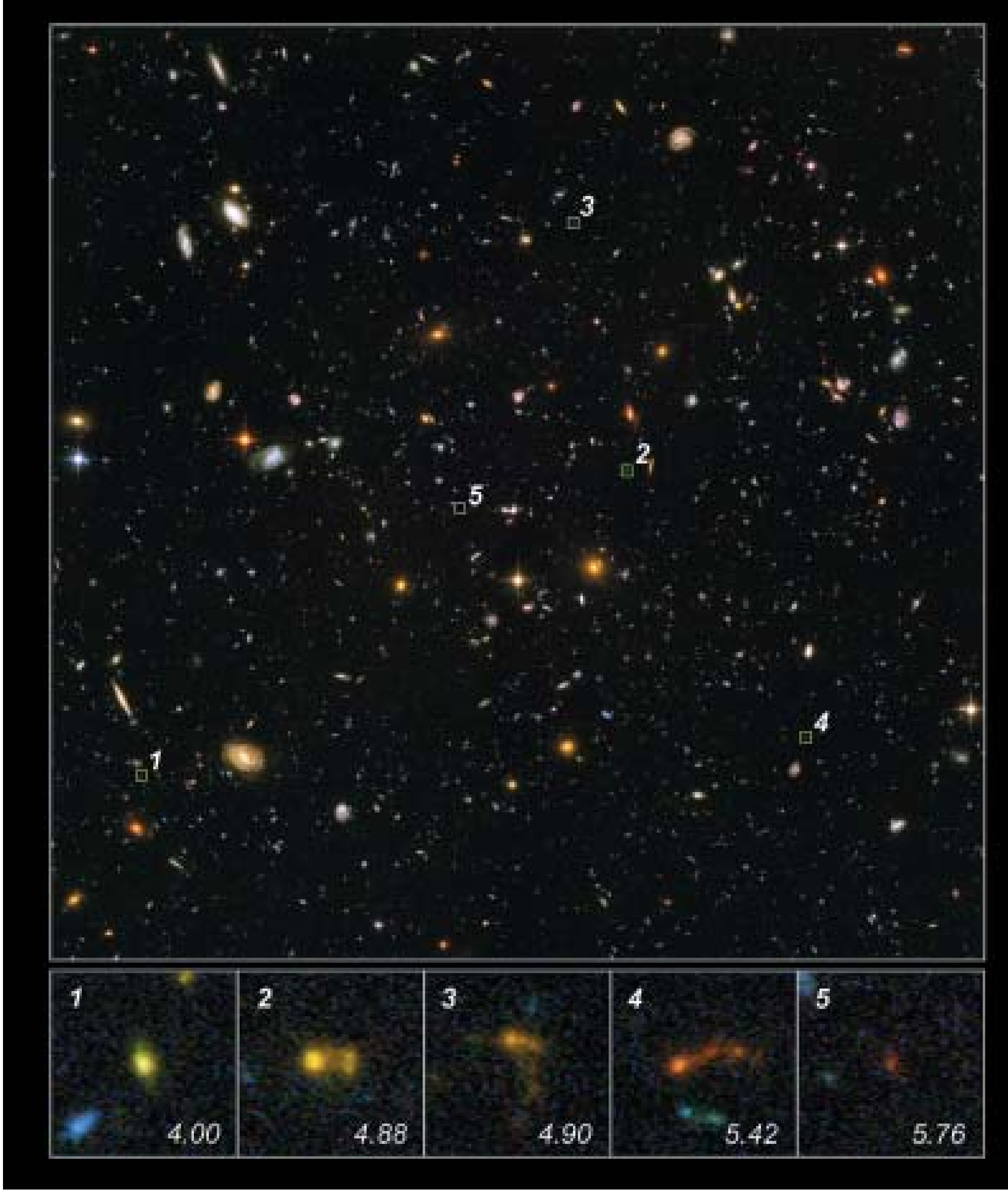
There is a type of supernova (called a Type 1a) that could provide such a 'standard candle'. Unfortunately such supernovae are rare. Typically, in any galaxy, such a stellar explosion only happens perhaps once in every 50 years, and you would have to be looking in the right direction when it happened. So, to get good measurements over a very long baseline, you have to look at a lot of very distant galaxies for as long as you can get.

Fortunately the Hubble Space Telescope provided such a sample through its deep field measurements. The Hubble Telescope was pointed at parts of the sky unobstructed by nearby stars or galaxies, and made to 'stare' until the faintest distant objects came into view.

In the late 1990s, the High-z (high redshift) Supernovae Search Team (led by Brian Schmidt) and the Supernova Cosmology Project (led by Saul Perlmutter) were using ground-based telescopes to find nearby supernovae.

Adam Riess, working for the Space Telescope Science Centre and the High-z Team, sifted through the Hubble Deep Field observations and discovered Type 1a supernovae at a much higher redshifts than had ever been discovered before (SN 1997ff).

This measurement at such a large distance allowed them to estimate the true expansion rate of the Universe. What they expected to find was either a constant expansion, or perhaps that the expansion rate was slowing down due to its internal gravitational field. What they found – what they did not expect to find - was that the expansion of the Universe was accelerating! It was as though some unseen pressure or energy was driving the components of the Universe apart at an ever-increasing rate. Now, as well as 'dark matter', cosmologists had 'dark energy' to contend with as well.



In this Hubble Space Telescope deep field image several objects have been identified as the faintest, most compact galaxies ever observed in the distant Universe. They are so far away that we see them as they looked less than one billion years after the Big Bang. Blazing with the brilliance of millions of stars, each is a hundred to a thousand times smaller than our Milky Way. The bottom row of pictures shows several of these clumps (distance expressed in redshift value). Three of the galaxies appear to be slightly disrupted. Rather than being shaped like rounded blobs, they appear stretched into tadpole-like shapes. This is a sign that they may be interacting and merging with neighbouring galaxies to form larger structures. The detection required joint observations between Hubble and NASA's Spitzer Space Telescope. Blue light seen by Hubble shows the presence of young stars. The absence of red light from Spitzer observations conclusively shows that these are truly young galaxies without an earlier generation of stars. NASA/ESA

Synthesis – you are here

Cosmologists build overall models of how the Universe evolves, depending on how much 'dark' mass there is in it, and how strong the 'dark energy' is. In some versions, the Universe collapses after a period of expansion. In some cases the Universe collapses too quickly to create planets like the Earth. In some possible Universes the mass-density makes Space strongly curved and 'closed' – finite in extent.

Estimates for the 'flatness' found from the microwave background, the rate of expansion, and the mass density of the Universe are only accurate to about 10 percent. But that is sufficient to plot on the chart 'where we are'. We can get an idea of how much 'dark matter' pervades Space, and how strong the 'dark energy' is, and hence our own history and future. What is most interesting about this story, however, is that most of the things that make up our Universe are invisible, but through the use of space-borne instruments they are no longer undetectable.