

UNSEEN UNIVERSE Michael Rowan-Robinson

NewScientist

DUST TO DUST

The most significant source of the infrared light that reaches Earth is the interstellar medium. This mixture of gas and dust pervades the space between stars in galaxies and has a temperature of 10 to 50 kelvin. It radiates only in the infrared, and dims the visible light from distant stars, reddening their colour.

The first direct image of the interstellar dust came in 1983 courtesy of the Infrared Astronomical Satellite (IRAS), a space telescope funded by the US, the Netherlands and the UK. It was a signal moment in astronomy. Observing interstellar dust allows us to glimpse the full cycle of stellar life and death, including the formation of new stars and planetary systems from the dust - sometimes in violent bouts as distant galaxies collide - long before these stars become visible to optical telescopes. A striking example lies in the pair of merging galaxies known as the Antennae, around 45 million light years from us: their brightest infrared regions (image left) are dark at visible

wavelengths (image right).

Infrared observations also reveal dying stars blowing off clouds of dust and gas, replenishing the interstellar medium. The dust is mainly silicates and amorphous carbon - sand and soot. The production of this dust is crucial to our existence: every carbon atom in our bodies was created in the core of a star, was ejected as that star died, and drifted around in the interstellar medium before being sucked into our solar system.

Star-forming regions of the Antennae galaxies show up in this infrared Herschel image

STAR INSTRUMENT: HERSCHEL

Most infrared wavelengths are absorbed by water and carbon dioxide in the atmosphere, with only a few narrow spectral "windows" of infrared reaching the ground. Infrared telescopes must therefore be situated at the top of mountains or, better still, in space.

The current top dog in the infrared pack is the European Space Agency's Herschel telescope, which started operating in 2009. It is the largest telescope ever launched into orbit, and carries a spectrometer and two cameras that cover wavelengths between 70 and 500 micrometres. All this equipment has to be cooled to temperatures close to absolute zero to prevent the telescope's own infrared emissions affecting the measurements.

As interpretation of Herschel data gets under way, the telescope is already delivering some spectacular images of filamentary interstellar dust clouds in which stars may be forming, as well as galaxies with unexpectedly large amounts of very cold dust missed by earlier studies. Herschel, the largest space telescope (right), is named after the founding father of infrared astronomy (below)





TZ/AFP/GETTY IMAGES-LEFT ABBOTT, LEMUELFRANCIS (C.1760-1803) VICTORI 4 AND NORTHEAST SOMERSET COUNCL/BRIDGEMANARTLIBRARY

INFRARED ASTRONOMY

As we look into a clear night sky, we see just a fraction of what the universe contains: mainly stars in our galaxy radiating in the narrow visible wavelength band between 390 and 750 nanometres.

Optical telescopes extend that vision to far-off galaxies, but it is only in the past century or so, as we have begun to observe the broad sweep of invisible electromagnetic wavelengths, that the full drama of the cosmos has been unveiled.

The first invisible radiation to be detected was in the infrared range, at wavelengths from 750 nanometres up to a millimetre. It was discovered in 1800 when the British astronomer William Herschel used a prism to split sunlight and saw the mercury of a thermometer placed beyond the red end of the spectrum begin to rise.

Infrared astronomy took off in the 1960s. It studies objects in the universe at temperatures between 10 and 1000 kelvin: asteroids, comets, interstellar dust and newly forming stars and galaxies.



OTHER WORLDS

The first dedicated infrared space telescope, IRAS, found discs of dust and other debris around some bright stars, pointing the way to searches for planetary systems. Infrared surveys have since detected many debris discs and planets in the process of forming.

Most fully-formed extrasolar planets are discovered by optical telescopes looking either at small changes in the star's velocity as the planet orbits it, or tiny drops

> in brightness as the planet crosses the surface of the star. Infrared instruments, such as NASA's Spitzer Space Telescope (left), have an important complementary role to play. They look for "hot Jupiters", close-orbiting massive planets, as they pass in front of their star.

An infrared instrument on the European Southern Observatory's Very Large Telescope was the first to provide a direct image of an extrasolar planet. This body, in orbit around a brown dwarf star, is five times the mass of Jupiter.

GALACTIC ORIGINS

Because infrared observations spy out stars as they form and die, we can use them to look back in time, tracing how stars and galaxies formed throughout cosmic history almost as far back as the big bang.

When NASA's Cosmic Background Explorer (COBE) space mission, launched in 1999, measured the total background radiation at millimetre and sub-millimetre wavelengths, it found a strong contribution from distant galaxies. It turns out that more than half of the energy emitted by far-off stars at optical and ultraviolet wavelengths is absorbed by dust and re-emitted in the infrared before it reaches us, making infrared essential for our understanding of the universe.

The infrared is also important for finding out how galaxies first arose. The universe is expanding, which means most galaxies are receding from us and the radiation they emit undergoes a Doppler shift to longer wavelengths. This "red shift" means visible light from the most distant galaxies known, emitted in the first billion years after the big bang, is stretched to infrared wavelengths by the time it reaches us.

Observing in the infrared requires sun shields to keep the instruments cool - and provide power



OUASARS

The first isolated celestial source of radio waves, Cyg A in the constellation Cygnus, was identified as a distant galaxy in 1954. By 1962 astronomers at the University of Cambridge had listed over 300 radio sources in the northern sky.

A few of these were remnants of supernovae in our galaxy, including an object - now known to be a pulsar - at the heart of the Crab nebula, the remains of a supernova explosion seen by Chinese astronomers in AD 1054. Most, however, were within distant galaxies. Some were associated with objects that looked like stars, and became known as guasi-stellar radio sources, or quasars. What these luminous, compact objects were was long controversial. Today we believe

them to be supermassive black holes at the centre of distant galaxies, with masses ranging from a million to a billion times that of the sun.

We now suspect that most galaxies, including our own, have a black hole at their heart, and that in radio galaxies and quasars this black hole is swallowing up the surrounding gas. As the gas spirals in towards the hole, magnetic field lines in the gas get wound up too, accelerating electrons and producing radio waves. More than 200,000 guasars are now known.

GALACTIC INTERACTIONS

Regular galaxies are suffused with hydrogen gas. As hydrogen atoms emit radio waves with a wavelength of 21 centimetres, radio telescopes can map this gas. Often it extends far beyond a galaxy's visible boundary and can even link objects that appear separate. An example is the M81 group of galaxies around 12 million light years away (pictured below). In an optical telescope these galaxies seem distinct, but radio observations show a web of hydrogen connects them, through which they tug at each other gravitationally.

We can get a wealth of information on the internal

dynamics of galaxies by looking at other spectral lines from interstellar gas molecules, for example in the microwave band, which lies between the radio and the infrared. Such observations reveal that dense molecular clouds have a rich chemistry, much of it based on carbon: more than 140 molecules have been identified, with carbon monoxide the most abundant after hydrogen.



PULSARS

In 1967, Jocelyn Bell and Antony Hewish (above) were studying emissions from guasars with a new radio antenna on the edge of Cambridge, UK, when Bell noted a pulsing radio signal repeating every second or so. It was the first of a new class of radio sources known as pulsars. These rapidly rotating neutron stars, the remnants of massive supernovas, have stupendous magnetic fields which can reach 10 gigateslas; Earth's field, by comparison, is a puny 50 microteslas. As they spin, pulsars emit synchrotron radiation in jets that sweep through space like a lighthouse beam, resulting in the pulsing signal seen by our telescopes.

Radio telescopes have found thousands of pulsars with periods ranging from a millisecond to several seconds. In 1974, the orbit of a pulsar in a binary system with an ordinary, non-pulsing neutron star was seen to be slowing down exactly as it would if it were emitting gravitational waves - the only indirect evidence we have so far of this key prediction of Einstein's general theory of relativity (see Instant Expert 1, "General relativity", New Scientist, 3 July).

"Identifying the sources of radio waves reveals some of the universe's most extreme objects"

STAR INSTRUMENT: THE VERY LARGE ARRAY

The classic image of the radio telescope is of an overblown television satellite dish. Famous examples include the steerable telescopes at Jodrell Bank in the UK, the Parkes Observatory in New South Wales, Australia, and the National Radio Astronomy Observatory at Green Bank, West Virginia. The largest single dish of them all is the fixed 305-metre-diameter dish at Arecibo in Puerto Rico, which famously featured in the James Bond film GoldenEve.

Even such a monster cannot pinpoint a radio source in the sky to the desired accuracy, however. To make high-resolution observations, you need a dish hundreds of thousands of times bigger than the radio wavelengths you are observing. This is done by combining the signals from many scattered dishes using a technique called aperture synthesis. The prime example of such an instrument is the Very Large Array in New Mexico, which consists of 27 dishes spread along three arms of a "Y", each 10 kilometres long. It can locate a radio source in the sky to an accuracy of around a 1/10,000th of a degree.

RADIO AND MICROWAVE ASTRONOMY

Radio and microwave telescopes study the longest electromagnetic wavelengths – anything longer than about a millimetre. Some of these emissions are produced by the coldest objects in the cosmos, such as the 2.7-kelvin background radiation from the big bang.

Most, however, are generated as "synchrotron radiation", given off when electrons spiral through magnetic fields at close to the speed of light. Identifying the sources of this radiation has revealed some of the universe's most extreme objects, such as pulsars and quasars.



Signals from the antennas of the Very Large Array in New Mexico (below) are combined to make detailed radio images, like this one of swirling hydrogen gas in the M81 galaxy group (left)

ROGERRESSMEYER/CORBIS-LEFTNRAD/

THE COSMIC MICROWAVE BACKGROUND

In 1965, while trying to make the first microwave observations of the Milky Way, Arno Penzias and Bob Wilson of Bell Labs in Holmdel, New Jersey, (below) found their instruments plagued by unexplained noise coming from all directions in the sky. This turned out to be one of the most important astronomical discoveries of the 20th century: the radiation left over from the big bang, known as the cosmic microwave background or CMB.

This radiation has a spectrum exactly like that of a body with a temperature of 2.73 kelvin, a spectacular confirmation of what the big bang theory predicts. Its strength is virtually identical no matter where you look: disregarding a systematic 1 in 1000 variation caused by our galaxy's motion through the cosmos, its intensity varies by no more than 1 part in 100,000.

These tiny fluctations are nonetheless important, as they provide a wealth of information about the abundance of different types of mass and energy in the universe. Measurements of the CMB by the Wilkinson Microwave Anisotropy Probe (WMAP) suggest just 4 per cent of the universe is ordinary matter, while

> 23 per cent is unseen dark matter, presumed to be made of unknown particles, and 73 per cent is the even more perplexing dark energy, whose nature remains a mystery.

> The European Space Agency's Planck Surveyor mission, launched in 2009 on the same rocket as the Herschel infrared telescope, will map the CMB in still more exquisite detail than WMAP, perhaps even detecting the fingerprint of gravitational waves left over from the early stages of the big bang.





STAR INSTRUMENT: FERMI

The international Fermi gamma-ray space telescope was launched in 2008. It will carry out a survey of the whole sky as well as studying gamma-ray bursts (see below), pinpointing their locations to within 1/60th of a degree.

Most of the gamma-ray sources will probably be supermassive black holes at the centre of galaxies, but Fermi will also study pulsars, supernova remnants and the general background of gamma rays that emanates from all corners of the cosmos and whose origin is not fully understood. Fermi might also detect interactions between the postulated dark-matter particles known as WIMPs, if they exist. It will also perform other tests of fundamental physics that can be carried out at these ultra-high energies, such as measuring whether the speed of light is the same at all wavelengths.

BURST ASTRONOMY

Gamma rays have wavelengths shorter than 0.01 nanometres and are emitted during radioactive decay, or by particles travelling near the speed of light. The first gamma-ray burst was detected in 1967 by satellites monitoring atmospheric nuclear weapons testing.

Most bursts probably occur when a massive, fast-spinning star collapses to form a black hole, sending out a narrow beam of intense radiation, while shorter bursts may be emitted when two neutron stars merge. Bursts typically last a few seconds, with a longer-lived X-ray and optical afterglow, but can release as much energy as our sun will radiate in a 10-billion-year lifetime. They are visible even from the edge of the visible universe: recently, rays were seen from a galaxy 13 billion light years away, meaning they were emitted just 600 million years after the big bang.

As with X-rays, gamma rays are absorbed by the Earth's atmosphere. A dedicated space mission, NASA's SWIFT telescope, has studied over 500 bursts since it was launched in 2004, while ground-based instruments such as HESS in Namibia, MAGIC in the Canary Islands and VERITAS in Arizona keep an eye out for light from showers of short-lived subatomic particles created when energetic gamma rays collide with atoms in the Earth's atmosphere. The HESS telescope spies gamma-ray bursts from the Namibian veld





X-RAY SUNS

Ordinary stars emit huge amounts of X-rays, as the American T. R. Burnight discovered in 1948 when he launched a captured German V2 rocket containing a roll of photographic film towards the sun. These come mainly from our star's corona, the outer envelope of hot plasma that is most easily seen during a total eclipse, and also from particularly active regions of the sun's disc.

Solar X-ray missions such as NASA's Solar and Heliospheric Observatory (SOHO), launched in 1995, and Yokhoh, a joint mission by Japan, the UK and the US launched in 1991, have been able to observe solar flares as they develop. The most powerful of these flares can result in coronal mass ejections where a huge bubble of highly energetic particles and magnetic field lines bursts away from the sun. These can potentially disrupt communications when they hit Earth, and also present a radiation hazard to astronauts on any future crewed interplanetary missions.

X-RAY AND GAMMA-RAY ASTRONOMY

X-rays and gamma rays are the most energetic electromagnetic waves, with wavelengths of a fraction of a nanometre or less.

Observations at these wavelengths show the universe at its hottest and most violent. This is a realm of gamma-ray bursts, of gas at temperatures of hundreds of millions of degrees swirling around the remnants of dead stars, and of fascinating objects such as white dwarfs, neutron stars and black holes.



DEATH STARS

Cosmic X-rays are absorbed by oxygen and nitrogen in Earth's atmosphere, so X-ray telescopes must be put into orbit. The first compact X-ray source, Sco X-1 in the constellation of Scorpio, was found during rocket observations of the moon in 1962. In 1970, the first dedicated X-ray satellite, NASA's Uhuru, was launched.

Many X-ray sources are binary star systems in which gas being shed by a dying star spirals into its companion – a dead, compact remnant of what was once a star. As it does so, it heats up and emits X-rays.

In Sco X-1 the companion object is a neutron star, the remnant of a star 10 times the mass of our sun. Other systems have larger, white-dwarf companions. But measurements in 1971 of the unseen companion's orbital wobble in one X-ray source, Cyg X-1 in the constellation Cygnus (pictured below), showed it was too heavy for a white dwarf or neutron star. It had to be a black hole - the first observational evidence of the existence of such a body.

X-rays are also emitted from the hot inner edges of discs of material accreting around supermassive black holes in active galactic centres and quasars (see p iv). Surveys by NASA's Chandra X-ray observatory and the European Space Agency's XMM-Newton satellite, both launched in 1999, have pinpointed thousands of such sources. One X-ray spectral line from highly ionised iron has been particularly informative: in some cases, it provides evidence of distortion due to the effects of general relativity.



X-ray images of the sun allow us to see the full spectacular effect of solar flares



Michael Rowan-Robinson

Michael Rowan-Robinson is professor of astrophysics at Imperial College London. He works principally on infrared and sub-millimetre astronomy, and cosmology. He contributed to the IRAS, ISO and Spitzer infrared space missions, and is currently involved with both the Herschel and Planck projects. He has been writing for *New Scientist* for over 40 years.



THE FUTURE OF THE UNSEEN UNIVERSE

The coming years will see more of the invisible universe revealed by existing instruments and new probes spanning all wavelengths.

The workhorse of current space astronomy, the Hubble space telescope, will cease to operate after 2014, at which time its successor, the James Webb Space Telescope, should be ready for launch. The JWST will operate mainly in the infrared, covering wavelengths from 500 nanometres to 24 micrometres. Its main aim will be to obtain images of Earth-sized planets and to detect the very first galaxies at the edge of the observable universe. Towards 2020, SPICA, a joint Japanese-European infrared space telescope, should also be well advanced, together with a slew of giant ground-based optical and near-infrared telescopes - the European Extremely Large Telescope, the Thirty-Metre Telescope and the Giant Magellan Telescope.

The Atacama Large Millimeter Array (ALMA) will span wavelengths from 0.4 to 3 millimetres and should come on stream in Chile in 2012. It will probe star-forming regions in our galaxy and others with exacting angular resolution and sensitivity.

Even ALMA will be surpassed in scale, though, by an international radio telescope known as the Square Kilometre Array (SKA). To be sited in South Africa or Australia, it will connect a dense central square kilometre of radio antennas with receiving stations up to 3000 kilometres away. Ambitions for SKA are mind-blowing: it will study cosmic evolution and the nature of dark matter and dark energy through observations of hydrogen gas in a billion galaxies, and perform fundamental measurements to test our understanding of gravity and detect gravitational waves.

At the X-ray end of the spectrum, NASA and the European and Japanese space agencies are investigating the feasibility of an International X-ray Observatory. If it goes ahead, IXO will peer through dust and obscuring clouds of gas to discover and map supermassive black holes back at times when galaxies were first forming, and uncover the history and evolution of matter and energy, both visible and dark. It will also investigate when and how the elements were created and how they became dispersed in the intergalactic medium.

RECOMMENDED READING

Night Vision by Michael Rowan-Robinson (Princeton University Press, to be published late 2010) *Finding the Big Bang* by P.J.E. Peebles, L. A. Page Jr and R. B. Partridge (Cambridge University Press)

WEBSITES

Infrared astronomy (Infrared Processing and Analysis Centre, California Institute of Technology: bit.ly/bhfGlb) Radio astronomy (US National Radio Astronomy Observatory: bit.ly/A5gA4) An introduction to X-ray astronomy (University of Cambridge Institute of Astronomy X-ray group: bit.ly/70yrUF)

Cover image: JAXA/ESA