ESA BR-170

February 2001

THE INFRARED REVOLUTION

Unveiling the Hidden Universe

esa

ABOUT ESA

The European Space Agency (ESA) was formed on 31 May 1975. It currently has 15 Member States: Austria, Belgium, Denmark, Finland, France, Germany, Ireland, Italy, The Netherlands, Norway, Portugal, Spain, Sweden, Switzerland and The United Kingdom. Canada is also a partner in some of the ESA programmes.

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Published by:
ESA Publications Division
ESTEC, PO Box 299,
2200 AG Noordwijk,
The Netherlands

Editor:
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Design and Layout:
Martin Kornmesser
(Hubble ESA Information Centre)

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Proof Reading:
Anne Rhodes

ISBN 92-9092-662-7

Printed in:
The Netherlands

Captions for part openings (pages 4, 14 and 32):

Part I
IRAS View of the Sky
The IRAS satellite surveyed most of the sky in the infrared. The image here is made of observations done at 100, 60 and 12 microns (red, green and blue colours). The most prominent features are due to cool dust in our Milky Way. Stretching across the entire sky is a S-shaped band of faint infrared light coming from cool dust in the Solar System.

Part II
COBE View of the Sky
The COBE satellite observed the sky at far-infrared (60-240 microns) and made this unique image. The cirrus-like pattern is due to infrared light from dust distributed throughout most of the Milky Way. Analyses show that a faint cosmic infrared background is also present in the observations.

Part III
Herschel and NGST
Two of the most promising infrared projects of the future.

THE INFRARED REVOLUTION

Unveiling the Hidden Universe

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THE INFRARED REVOLUTION

Humans have been pushing back the frontiers of their world ever since they left the plains of Africa. In just the last few hundred years they have discovered that the Earth is orbiting the Sun, that the Sun is just one of the two hundred billion stars that form the Milky Way galaxy, and that there are many more galaxies in the Universe. Powerful telescopes can now look out to frontiers as remote as ten billion light-years from Earth. Although the observable Universe has become very large indeed, astronomers realised some decades ago that their view of the cosmos was, at best, only partial. It was not just a matter of seeing farther out, but also of using different eyes, eyes able to see other kinds of light or radiation.

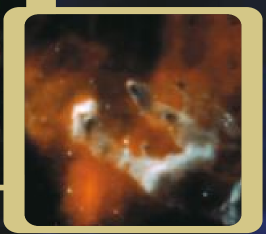
Infrared light was discovered exactly 200 years ago by the Anglo-German astronomer William Herschel, but telescopes only began to explore the infrared Universe forty years ago. These new observations have revolutionised astronomy, revealing previously hidden aspects of the Universe that have once again changed our perception of the world around us. The infrared Universe has proved amazingly rich and diverse. It has given us keys to unlock the chemistry of the Universe, to explain how stars are born and to establish the origin of galaxies. The use of infrared technology in astronomy is now well advanced and the infrared revolution is in full swing. But there is much more to come. The golden age of infrared astronomy has just begun.

Europe has a long-standing involvement in infrared astronomy, but only took the lead in this field after the launch of the European Space Agency's (ESA) Infrared Space Observatory (ISO). Although ISO stopped observing in May 1998 its observations have never been used more actively than now. In 1997 ESA's participation in the NASA/ESA Hubble Space Telescope gave Europe access to an important high-resolution near-infrared instrument called NICMOS (Near Infrared Camera and Multi-Object Spectrograph).

ESA is also very active in future infrared astronomy projects. It is launching the Herschel Space Observatory and participate in the NASA/ESA/CSA Next Generation Space Telescope (NGST), which is the infrared successor to the Hubble Space Telescope.

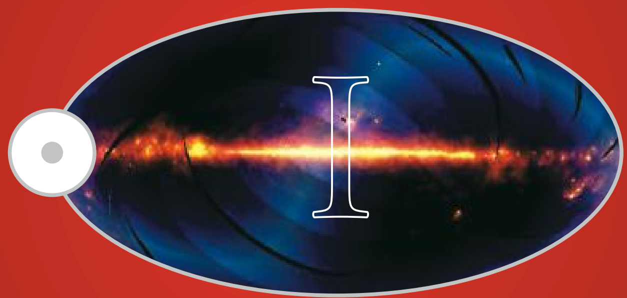
Infrared astronomy is young and booming, with a large number of current, challenging projects in space and on the ground. To give a full account of them all, as well as of all the infrared discoveries made so far, would be too ambitious a goal and is not the purpose of this brochure, which focuses on missions involving ESA. We hope that these pages will give a glimpse behind the scenes of infrared astronomy as the curtain rises on ever more exciting discoveries and will be enjoyed by all those who have thrilled to the joys of discovery, however small.

NGC 7027: Hubble/NICMOS



Eagle Nebula: ISO/ISOCAM

Part I SEEING INTO THE INFRARED

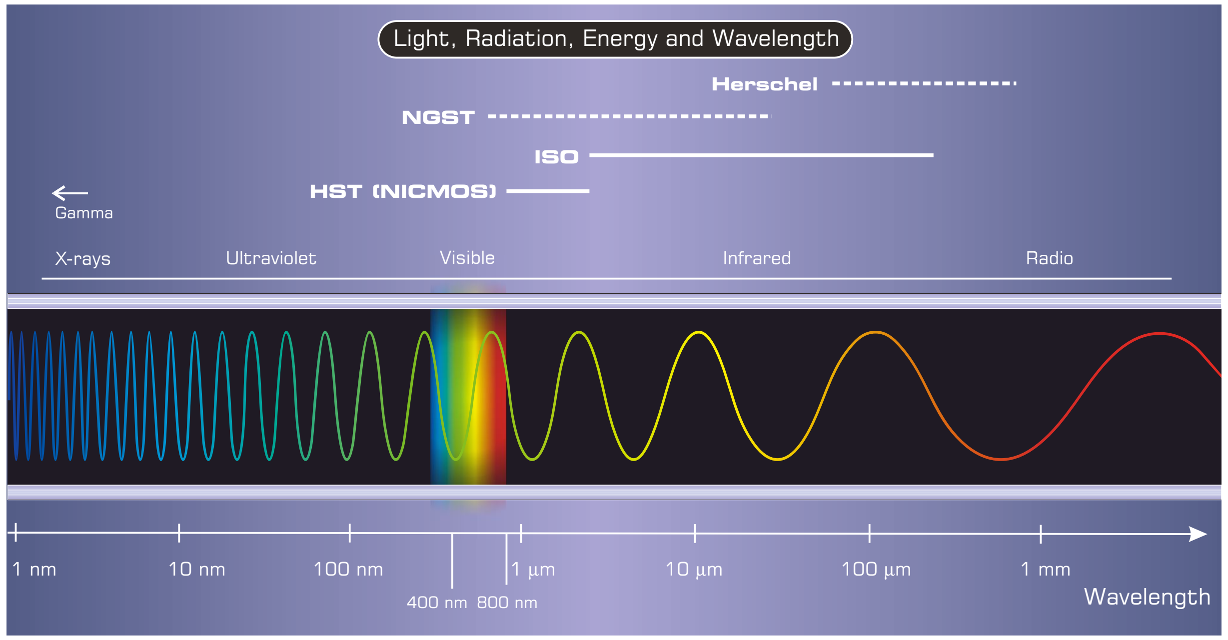


Infrared radiation is a type of light. The term 'light' is usually associated with colour and brightness, but there are types of light which are invisible to the human eye: gamma rays, X-rays, ultraviolet light, infrared light, microwaves and radio waves. The human eye is 'tuned' to detect only visible light, and therefore misses all these other types of electromagnetic radiation.

All types of light are 'electromagnetic radiation'. Electromagnetic radiation propagates through space as a wave. Although this wave always travels at the same speed in a vacuum (the famous speed of light, 300 000 kilometres per second), some of its characteristics vary depending on its energy. Ultraviolet radiation, for instance, is more energetic than visible light, which in turn is more energetic than infrared radiation.

Astronomers, for natural reasons, first studied the sky using visible light, but as science and technology have become more sophisticated, radiation from other parts of the electromagnetic spectrum has also come into play. Infrared radiation is the most recent to be exploited, thanks to a combination of new developments in detector technology and the advent of space-based telescopes.

The illustration below relates the characteristic length (the wavelength) of the light waves, to the energy of the individual light particles or photons. Notice that visible light has a wavelength of a few tenths of a micron (a micron (μm) is a thousandth of a millimetre) and occupies a remarkably small part of the whole electromagnetic spectrum. Infrared light lies between the red end of the visible and the microwave part of the electromagnetic spectrum. It can have wavelengths ranging from just less than 1 micron (near-infrared) to about 1 mm (sub-millimetre waves). In daily life, infrared radiation has numerous uses: in remote controls, police speed measurement systems, night-vision binoculars, security systems, auto-focus cameras, and car door locks, to name but a few.



This illustration shows the different kinds of light, or so-called electromagnetic radiation. The 'size' of the light waves – the wavelength – increases towards the right. The energy of the light increases towards the left, meaning that the shorter the wavelength of the light, the higher the energy it has. The wavelengths at which two famous infrared projects, ISO and NICMOS, observed are also shown in the figure, as well as the two future missions, Herschel and NGST.

Cat Seen in Infrared

SIRTF Science Center

An infrared photograph of an animal enhances features according to their heat emission: a cold nose appears very dark, whereas the warm eyes and ears show up brightly.

THE COLD UNIVERSE

Astronomers have used several different properties of infrared light to reveal more about the Universe. Although our eyes cannot see infrared radiation we can sense it – as radiant heat.

Infrared radiation 'is' heat, and all objects, even the coldest ones – for example an ice-cube – emit a certain amount of heat. In fact, cold objects – up to temperatures of about 3,500°C – radiate most of their energy at infrared wavelengths. The cool Universe is therefore best studied in the infrared. Hotter objects like the Sun (which has a surface temperature of about 5,800°C) radiate strongly at more energetic (shorter) wavelengths. The Universe is full of cool objects, including aging stars, planets and dust, none of which generally shine brightly in the optical part of the spectrum and could not be observed directly until sensitive infrared detectors came along.

THE CHEMICAL UNIVERSE

The chemical make-up of dust clouds and other interesting regions can be probed by looking at the spectra of the molecules in the region (see box about Astronomical Tools). Very often the spectra can only be obtained by observing in the infrared. The reason is that most atoms and molecules emit radiation whose energy corresponds to the infrared range (emitted through rotations and vibrations). Besides, infrared radiation is typical of cooler regions, for instance dust clouds, where more complex compounds, such as organic molecules are often found. Infrared astronomy has made many interesting discoveries related to these more complex molecules in space.

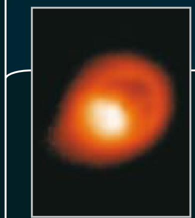
ASTRONOMICAL TOOLS

Astronomy is an unusual science in that it must rely only on observations of the radiation reaching us from celestial objects. Two different tools are used to observe the light and to extract the maximum amount of information: images and spectra.

***Images** are optical representations of objects. Two characteristics for a given image are the field of view and the resolution of the image (both measured in degrees or arc-seconds (1/3,600 degree). The field of view is a measure of how large a chunk of sky fits in one image. The resolution is a measure of the 'sharpness' of an image. Images are essential to give an idea of the different processes taking place in a given region.*

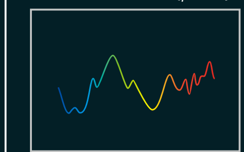
*Light can be 'split' into its constituent colours using an instrument called a 'spectrograph'. A similar phenomenon happens when a rainbow is formed. When the light emitted or absorbed by atoms and molecules goes through a spectrograph the resulting pattern of 'coloured' lines is called a **spectrum**. Each compound produces a different spectrum, which can therefore be used as an identifier: a true 'chemical fingerprint'. Spectra are thus the astronomer's favourite tool to reveal the composition of objects in the Universe.*

An image (showing organic molecules around a star).



ISO/ISOCAM

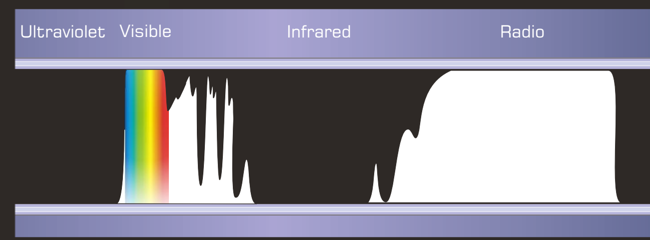
A spectrum showing absorption lines (troughs) and emission lines (peaks).



ESO & Joao Alves, Richard Hook and Bob Fosbury

A Cool Dusty Cloud Filled with Interesting Chemistry

The visible/near-infrared image of the dust cloud seen to the left illustrates three out of four main themes in infrared astronomy.
1. Dust: The dust in the cloud has blocked (scattered) almost all blue light and is letting only the reddest part of the starlight through. In fact only infrared light is allowed to pass, which is why the stars behind the cloud are coloured (infra)red in a rather dramatic way. The stars are not visible in optical images.
2. Cool temperatures: These dust clouds are cool objects and emit most of their light in the infrared. The red colour in the image corresponds to 2.2, the green to 0.8, and the blue to 0.4 micron.
3. Chemistry: The elements and compounds in cool clouds like this one are best studied with infrared telescopes and instruments.



ABOVE THE ATMOSPHERE

The Universe emits a tremendous amount of information in the form of different types of electromagnetic radiation. Only a small fraction of this is visible from the Earth (white areas) as the atmosphere absorbs the rest before it reaches the ground (black areas). Water vapour, ozone and carbon dioxide in the atmosphere absorb large parts of the infrared spectrum so most infrared astronomical observations have to be carried out at high altitude by instruments mounted below balloons or in rockets or spacecraft. The higher above the atmosphere an infrared telescope is, the better the observing conditions.
Apart from problems with atmospheric absorption, the atmosphere is itself also a source of infrared radiation, with a typical temperature of 10°C, making infrared observations of the coolest objects in the Universe difficult from the ground.

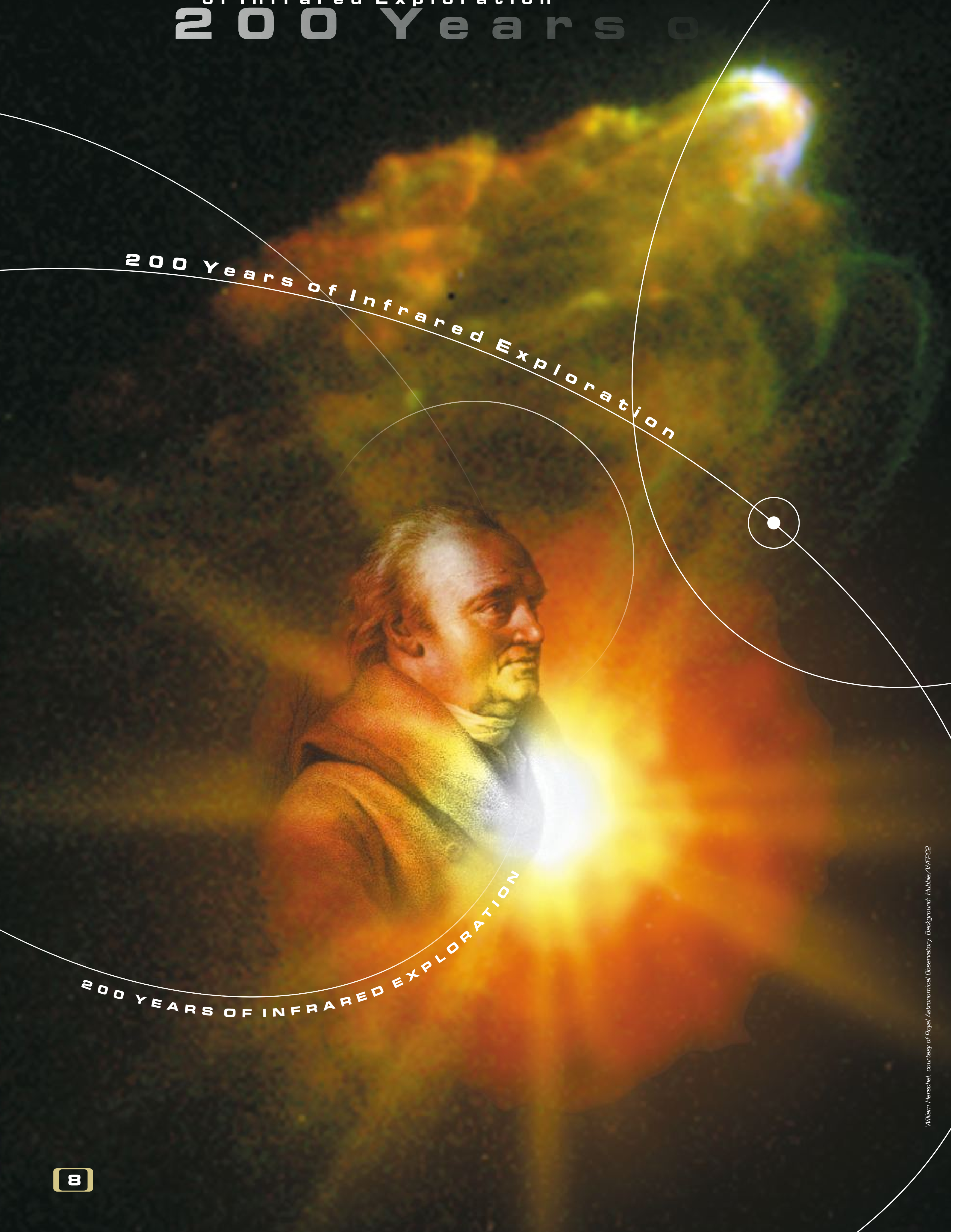
THE DUSTY UNIVERSE

Dust is the bane of the optical astronomers' life, blocking their view of many interesting objects. The Universe is full of dust, microscopic particles of varied composition – carbon, silicon, water ice, minerals, frozen carbon monoxide, organic compounds, silicates – the list is almost endless. The particles can be hard or soft and come in many different shapes, but the particle size is usually less than 1 micron. The wavelength of visible light is much the same size as many dust particles, so that visible light is very readily blocked (scattered) by the dust, whereas the longer wavelength infrared radiation passes through unhindered and the dust is therefore invisible to it.

However, the dust itself is also a source of infrared radiation that can be picked up by terrestrial detectors. For example, dust grains around a star absorb the starlight so that the dust begins to warm up and to radiate in the infrared. This absorption of energetic radiation and reemission at less energetic wavelengths is very efficient and dust clouds emit the majority of their energy at infrared wavelengths.

THE DISTANT UNIVERSE

Infrared radiation can help us to learn much more about the young, distant Universe. As a result of the Big Bang (the event that marks the beginning of our Universe), the Universe is expanding and most of the galaxies within it are moving away from each other. The more remote a galaxy is, the faster it is moving away from us. As an object moves away from us, the light that it emits is redshifted – the wavelength of the light is stretched and lengthened so that it is shifted towards the red part of the spectrum. The more distant the object, the greater the redshift. For distant galaxies this effect can be so large that they are only detectable in the infrared region.



William Herschel, courtesy of Royal Astronomical Observatory. Background: Hubble/WFPC2

As recently as 200 years ago the Earth was widely thought to be only about six thousand years old – in 1650 Bishop Ussher had famously calculated the date of creation as 4004 BC. The first to recognise the true age of the Earth was a Scottish physician called James Hutton, an amateur geologist, who, in 1790, realised from his study of rock formations that the Earth had to be much older. It was so many millions of years older than previously imagined, that it made Hutton's head spin to be "looking so far into the abyss of time". *Geology was not the only science at that time to radically revise and expand the view of the world around us. An unexpected discovery made by an astronomical contemporary of Hutton's would later lead astronomers to revise their view of the Universe just as dramatically.*

In 1800, the German-born British astronomer and musician, William Herschel – famous for his discovery of the planet Uranus a few years earlier – described that the differently coloured filters through which he observed the Sun allowed different levels of heat to pass. He performed a simple experiment to study the *"heating powers of coloured rays"*: he split the sunlight with a glass prism into its different constituent rainbow colours and measured the temperature of each colour. He observed an increase in temperature as he moved a thermometer from the violet to the red part of the 'rainbow'. Out of curiosity Herschel also measured temperatures in the region just beyond the red colour, where no light was visible, and to his surprise, he recorded the highest temperature there. He deduced the presence of invisible *"calorific rays"*.

Today these invisible rays are called infrared radiation. All objects emit infrared radiation and much can be learned about an object from this emission. However, the true significance of infrared radiation for astronomy was not immediately apparent. Although the first instruments to detect the invisible light were built soon after Herschel's experiment, not even the Moon was observed in the infrared until 1856. Astronomers had to wait a further one and a half centuries to experience the full startling impact of the sky revealed in the infrared.

Much more to be seen

The first infrared technology was not developed for scientific purposes, but for military applications. Infrared detectors can 'see' heat-emitting bodies at night to give a kind of 'night-vision'. This has great military importance and was the main impetus behind the development of infrared detectors during much of the twentieth century.

Only in the sixties were these new detectors pointed at the sky, and even then infrared astronomy was just expected to be an adjunct to optical astronomy. "*Stars, after all, were known to be visible objects; and the Universe appeared to be an aggregate of stars*", writes US infrared pioneer Martin Harwit in the book "A Century of Space Science".

The first infrared survey of the sky, performed by Gerry Neugebauer and Robert Leighton – who built their own telescope for the purpose – changed this view completely. The results were published in 1965 and Harwit describes them as *"electrifying"*: they revealed ten objects that were completely invisible to other existing telescopes, which merely detected visible (optical) light.

This raised an unsettling question: if a first look at the infrared sky had yielded about ten new, odd, infrared-bright objects, what would more detailed observations reveal? In 1969 the first catalogue of infrared-bright objects was published, including thousands of intriguing objects never seen before. A few years later more observations revealed the existence of distant galaxies whose radiation is stronger in the infrared than in the visible. There was no immediate explanation for this.

Astronomers were seeing a qualitatively different sky, a sky with different rules from the familiar night sky. The brightest objects in the night sky, visible to the human eye and optical telescopes, are typically those hot enough to emit light in the visible range. Furthermore, only those objects whose light is not absorbed by intervening dust can be seen. In contrast, in the infrared sky, both cold and dusty objects may outshine the optically bright ones. The first infrared observations surprised everyone by revealing many more infrared-bright objects in the sky than expected.

IRAS

Dimensions (HxWxD) — *3.6 x 3.2 x 1.7 metres*

Mirror size – *0.57 metre*

Weight – *1,000 kg*

Mission life – *25 January 1983 - 23 November 1983*

Orbit – *Sun-synchronous, near-polar, near-circular orbit at about 900 km altitude*

Instruments – *Survey Array, LRS (Low Resolution Spectometer), and Chopped Photometric Channel*

Temperature of instruments – *-269°C*

Wavelength coverage – *8 to 120 microns*

Collaboration – *IRAS was an international project involving the Netherlands, USA and the UK.*

ISO

Dimensions (HxWxD) – *5.3 x 3.5 x 2.8 metres*

Mirror size – *0.6 metre*

Weight – *2,400 kg*

Mission life – *17 November 1995 - 16 May 1998*

Orbit – *Highly elliptical between 1,000 km and 70,500 km altitude*

Instruments – *ISOCAM (an infrared camera), ISOPHOT (a photo-polarimeter), SWS (Short-Wavelength Spectrometer) and LWS (Long-Wavelength Spectrometer)*

Temperature of instruments – *-269°C*

Wavelength coverage – *2.5 to 240 microns*

Collaboration – *ISO is an ESA project with instruments funded by ESA Member States (especially the PI countries: France, Germany, the Netherlands and the United Kingdom) and with the participation of ISAS and NASA.*

NICMOS (HUBBLE)

Dimensions (HxWxD) – *(Only NICMOS instrument) 2.2 x 0.9 x 0.9 metres*

Mirror size – *(the Hubble Space Telescope) 2.4 metre*

Weight – *(Only NICMOS instrument) 370 kg*

Mission life – *February 1997 - November 1998 (extension planned from late 2001)*

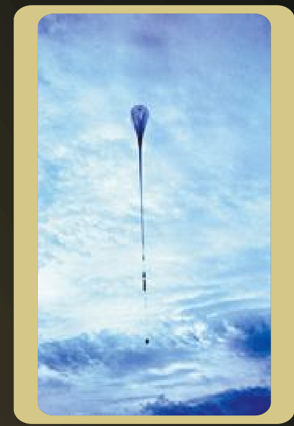
Orbit – *Circular, 593 km, inclined at 28.5 degrees to the Equator*

Temperature of instrument – *-213°C*

Wavelength coverage – *0.8 to 2.5 microns*

Collaboration – *The Hubble Space Telescope is a collaboration between ESA and NASA.*

Early Balloon Flight



Smithsonian/NASM

Observations with infrared telescopes carried by balloons started in the sixties. These balloons reached altitudes of more than 40 kilometres and helped to overcome some of the worst problems associated with atmospheric absorption.

A Slow Beginning

There were still serious hurdles for infrared astronomy to overcome. The Earth's atmosphere blocks most of the infrared light from the sky and the atmosphere itself emits strongly in the infrared. Ground-based infrared astronomers have to try to observe objects that can be a million times fainter than the emission from the sky – as difficult as trying to observe faint stars during the day with an optical telescope.

A deep exploration of the infrared sky required observations from above the atmosphere. How could this be done? There were several possibilities: detectors carried high by balloons, telescopes onboard aircraft and rockets... or a free-flying, space telescope.

The first balloons, launched in the sixties, reached altitudes of more than 40 kilometres. Infrared telescopes, carried by aircraft, followed a decade later. Both strategies provided the first infrared views of the centre of our Galaxy, but the detectors were still not completely lifted above the atmosphere. To see the full infrared sky astronomers needed to reach even higher, using rockets.

This was far from simple. The first launch of an infrared telescope onboard an Atlas rocket as part of a US Airforce military test mission was unsuccessful. An infrared detector working in space has to be cooled to very low temperatures so that its own infrared emission does not outshine the astronomical objects. This cooling requirement is not so strong for ground-based observations because the emission from the atmosphere is already stronger than that of the detectors themselves. In space, cooling is a key requirement that can be achieved by using liquid nitrogen (-196°C) or liquid helium (-269°C) to cool the instruments. Unfortunately these fluids evaporate very quickly.

The liquid nitrogen for the first rocket-borne infrared telescope was meant to last only six hours, so the nitrogen tanks were filled shortly before the scheduled launch time. Then the launch was delayed... by precisely six hours! When the rocket finally lifted off the temperature of the detectors was already too high for them to function. Harwit was leading the project and recalls the moment as *"heartbreaking"*.

The Jump to Space

Although "*pioneering rocket astronomy was not a happy venture*" as Harwit says, subsequent flights went much better. He remembers the thrills of the first succesful rocket flights when the first liquid-helium-cooled telescope revealed five distant sources near the centre of our Milky Way, all shining more brightly in the infrared than had ever been imagined. Rockets could reach an altitude of about 250 kilometres, providing at least five valuable minutes of observing time above the atmosphere. But, obviously, infrared pioneers dreamt about the long periods of observing time – months, or even years – that a true space telescope could provide. They started to push for such a facility.

The Infrared Astronomical Satellite (IRAS) was undertaken as a joint project of the US, the UK and the Netherlands at about this time. Its main goal was to perform a complete, sensitive survey of the whole sky at several infrared wavelengths.

Many astronomers doubted whether the technology was ready for such a challenge and building IRAS proved a complex undertaking. IRAS was launched in 1983 and was a great success from the very beginning. The telescope itself was 57 cm in diameter, cooled to -269°C and operated for 11 months.

As a result of IRAS about 250,000 infrared objects were catalogued, many of them opening up whole new areas of research, and posing many unexpected questions. What was the nature of the completely unknown population of galaxies, much brighter in the infrared than in the optical, discovered by IRAS? How many other stars were encircled by discs of dust, such as the one IRAS detected around the star Vega?

It was clear that the new science of infrared astronomy was here to stay. Even before IRAS had been launched, the European Space Agency (ESA) had started preliminary studies for a possible 'successor', which was approved shortly after IRAS' launch and was called ISO (Infrared Space Observatory).

The Birth of ISO

In February 1983, more than one hundred astronomers and space scientists, mostly European, gathered at a workshop in Scheveningen, in the Netherlands, to introduce the scientific community to the five different proposals for ESA's next space mission. Only one of the five, which included ISO, was to be selected by ESA's Science Programme Committee a few months later. The lobbying for each mission was intense.

Then, "*chance played in ISO's favour*", recalls Martin Kessler, ISO Project Scientist. "*The launch of IRAS had to be postponed to January 1983, so that the meeting at Scheveningen coincided with the early orbit phase of IRAS. We, the ISO people, were sitting there, hoping desperately that IRAS could prove that the infrared technology worked well. At one stage one of the main scientists involved with IRAS came in holding the results of the first IRAS scans across the galactic plane. He exclaimed 'The damn thing works!' or some such thing. IRAS was clearly working exceptionally well! ISO would probably have been selected in any case, but it was a helpful coincidence*".

Even during the development phase of IRAS a large number of European astronomers were thinking about a follow-up for the results from this satellite. If the IRAS surveys were successful "*it was clear that we had to go back and look in detail with a much higher resolution*", Kessler says. This was ISO's goal: to focus on and take a much 'closer' look at the most interesting regions seen by IRAS. The decision was taken unanimously by ESA's experts, and gave Europe a major lead in the discipline of infrared astronomy.

The Launch of ISO

ESA

ESA's Infrared Space Telescope, ISO, was put into orbit in November 1995, by an Ariane 44P launcher from the European Spaceport in Kourou, French Guiana.

However, ISO's selection as an ESA mission was controversial. Many thought that the technological challenges were too great for such an expensive mission. Parts of ISO had to be cooled to temperatures close to absolute zero, not a trivial technological task. Especially considering that the detectors and cooling system – the so-called 'cryogenics' – used on IRAS had been developed by the US part of the team, so there was a lack of obvious European expertise in this area. The four instruments onboard ISO were to be developed by multinational teams with leaders in France, Germany, the Netherlands and the United Kingdom. The satellite itself was built by an industrial consortium of 32, mostly European, companies.

Fortunately ISO exceeded expectations. When ISO was launched in November 1995 the mission life expectancy was only 20 months – dictated by the need to keep the telescope and instruments cold. The cryostat, a huge thermos flask surrounding the telescope and its instruments, was filled with 2,300 litres of superfluid helium as a coolant. The rate at which this helium evaporated would determine the lifetime of the mission. The original estimates turned out to be pessimistic and the satellite's working life stretched to more than 28 months.

ISO's 'eyes' did indeed see much deeper than IRAS. Some 600 teams from all over the world made observations with ISO during its operational lifetime and many astronomers continue to use the ISO data made public through the ISO Archive. "*There's general agreement that ISO worked exceptionally well in all areas – operational, technical and, above all, scientific. It solved questions triggered by IRAS, and of course also left a legacy of new mysteries for future infrared space missions to solve*", summarises Kessler.

NICMOS Before Launch

Ball Aerospace

NICMOS, the near-infrared camera and spectrograph for the Hubble Space Telescope.

NICMOS Comes to Life

IRAS mapped nearly all the sky in four broad infrared bands or 'colours', revealing the existence of several completely new classes of infrared objects and giving astronomers a detailed catalogue of interesting positions on the sky. ISO looked at individual sources with much higher sensitivity and greater spatial and spectral resolution than IRAS to detail the individual characteristics of the various targets. However, with a mirror size of 57 cm, ISO gave less sharp images and discerned less of the detailed structure than would be possible with a larger telescope. Thus, astronomers at the University of Arizona proposed using the Hubble Space Telescope, the telescope with the sharpest vision, to take near-infrared images of these newly discovered objects.

Hubble was not originally designed to make infrared observations, so Rodger Thompson (University of Arizona) and his team designed a new instrument for Hubble, the "Near Infrared Camera and Multi-Object Spectrograph" (NICMOS). This instrument is a combined camera and spectrograph and was attached to Hubble by astronauts during the Second Servicing Mission in 1997. To cool an infrared instrument attached to Hubble to temperatures as low as -213°C is not an easy task. Originally, NICMOS was cooled by a big block of nitrogen ice, which kept the instrument cold for almost two years before the ice evaporated. A new mechanical cooling device that does not need nitrogen ice – a so-called cryo-cooler – will be attached to NICMOS during the next Servicing Mission.

The combination of Hubble's very high resolution and the ability of infrared light to penetrate dust clouds, opaque to visible light, has allowed astronomers to study the nuclei of galaxies and dust-enshrouded star-forming regions and has led to the discovery of objects that are most probably nascent planetary systems.

Ground-based Near-infrared Image

ESO VLT/ISAAC

The star-forming region NGC 3606 imaged with the ESO ISAAC instrument on VLT Antu in Chile. The image demonstrates very clearly that certain types of near-infrared imaging are possible from the ground.

Infrared Astronomy Timeline

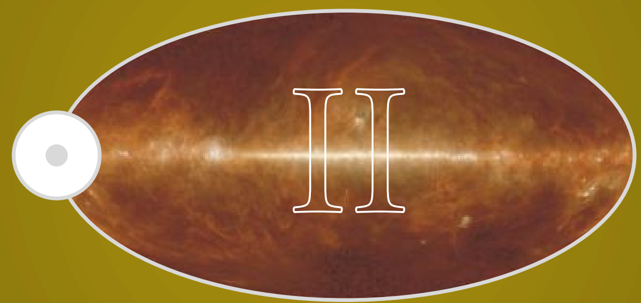
Ground-based

- **1800** William Herschel discovers infrared radiation.
- **1960s** Infrared observations from the ground start to provide important results. Notably the Two-Micron Sky Survey from 1965 makes a significant impact.
- **1980s** Infrared detectors with many detector elements ('pixels') are developed and spark a leap in observational sensitivity.
- **1996** The DENIS Project (DEep Near Infrared Survey of the Southern Sky) begins. A survey of the entire Southern sky at 0.8, 1.25 and 2.12 microns using a 1m ground-based telescope in Chile.
- **1997** The 2MASS (Two Micron All-Sky Survey) project begins. A survey of the entire sky at 1.25, 1.65 and 2.17 microns using two ground-based telescopes in Arizona (US) and Cerro Tololo (Chile).
- **1998** SCUBA (Submillimetre Common User Bolometer Array), an instrument working at submillimetre wavelengths, is mounted on a telescope on Hawaii.
- **1999** ISAAC (Infrared Spectrometer and Array Camera) mounted on the Very Large Telescope starts operation.

Air- and Space-based

- **1960s** Balloon-borne infrared telescopes start to deliver valuable results.
- **1970s** Cooled telescopes are launched into space on rockets.
- **1974** First observations with the Kuiper Airborne Observatory (KAO), a jet transport aircraft carrying an infrared telescope.
- **1983** IRAS (Infrared Astronomical Satellite) is launched.
- **1989** Launch of NASA's satellite Cosmic Background Explorer (COBE). COBE observed the cosmic background radiation – radiation emitted shortly after the Big Bang.
- **1995** Launch of Infrared Telescope in Space (IRTS), Japan's first infrared satellite.
- **1995** Launch of ESA's Infrared Space Observatory (ISO).
- **1996** The US Air Force satellite Midcourse Space Experiment (MSX) is launched.
- **1997** The NASA/ESA NICMOS (Near Infra-Red Camera and Multi-Object Spectrometer) is attached to the Hubble Space Telescope.
- **2000** NASA's SWAS (Submillimeter Wave Astronomy Satellite) is launched.

Part II THE INFRARED UNIVERSE



Deciphering the History of the Solar System

Our closest neighbours in space are eight planets, more than 50 moons and thousands of asteroids and comets that together with the Earth circle the Sun. They make up a tiny, but rich sample of the diversity of the Universe. The size of the planets in our Solar System ranges from small, rocky Mercury to the massive gas giants, Jupiter and Saturn. The varied environments of the moons include powerful erupting volcanoes, frozen surfaces that could hide liquid oceans and thick atmospheres similar to the atmosphere on Earth before life began. For all their external differences these bodies – even the Sun – were all made from the same raw material, drawn billions of years ago from a cloud of gas and dust called the 'protosolar nebula'. How did this transformation take place? Astronomers still don't have a clear picture of the early Solar System and would very much like to be able to replay the whole sequence of events in quick-time to answer the question. Recent infrared observations have gone some way towards solving the mystery.

The story of the Solar System begins about 5 billion years ago, as the Sun – for reasons the scientists have yet to agree upon – condensed out of the protosolar nebula. Once the central star had formed, the residual material from the protosolar nebula settled into a flat disc around the newly-born Sun. Tens of millions of years later this disc of left-over dust and gas became the planets, moons, asteroids and comets of our Solar System.

Solar System expert Th r se Encrenaz (Observatoire de Paris) comments, "*Infrared instruments are particularly suitable for Solar System studies, as the objects in the Solar System are cold and radiate most of their energy in the infrared range. In addition, the infrared region is ideal for analysing the chemical composition of planetary atmospheres, which, in turn, is a key to the understanding of the formation and evolution of the Solar System*".

Infrared telescopes can reveal processes that no one even suspected were taking place. Even the very first infrared observations of planets, back in the mid-sixties, produced surprises. Infrared-pioneer Frank Low found that Jupiter had an intrinsic infrared glow, which was the first indicator that Jupiter, Saturn and Neptune all have internal sources of heat.

Rain on the planets

The improvement of infrared detectors in the seventies allowed astronomers to begin detailed studies of the chemistry of planetary atmospheres – an area where the latest infrared space missions have contributed enormously. One example is the unexpected detection of water in the upper atmospheres of the gaseous planets by ESA's Infrared Space Observatory (ISO) in 1996, which, in turn, led to the discovery that water from space is constantly 'raining' down on all planets, including our own.

ISO detectors registered a continuous replenishment of water in the upper atmospheres of the giant planets, an influx of as much as 10 litres of water ice per second in the case of Jupiter. Where had this water come from? It was not thought to come from the planet itself, as Helmut Feuchtgruber (Max-Planck Institut f r Extraterrestrische Physik) explains: "*The upper atmosphere of the Earth is very dry, since water vapour rising from the oceans or the land freezes into clouds at a far lower altitude. We would expect the same kind of 'lid' to seal the water vapour of the outer planets. Therefore, any water vapour that we saw in the upper atmospheres of Jupiter, Saturn, Uranus and Neptune has had to come from the outside.*"

Only a few years ago further measurements of other planets, as well as the discovery – also by ISO – of water vapour in the atmosphere of Jupiter's moon Titan, confirmed that the planets really are being 'watered'. The water comes from interplanetary dust, which is full of the scattered grains of comet debris that are themselves mostly made of water ice.

Reconstructing the past

Learning more about the state of the Solar System today helps astronomers to reconstruct its past. Some observations are specially tailored for that purpose. For instance, the study of the chemical element deuterium – an isotope of hydrogen – in the atmospheres of Jupiter, Saturn, Uranus and Neptune aims to shed light on the initial composition of the cores and atmospheres of these planets.

The formation of the gaseous planets began when solid, icy particles – a common raw material in the young Solar System – started to clump together. They formed the massive cores of the planets, which then gravitationally attracted the gas that makes up the thick atmospheres we see today. The proportion of deuterium in these atmospheres tells astronomers much about the formation of the giant planets, because it can be compared with the proportion of deuterium in the composition of the protosolar nebula. An excess of deuterium suggests, for instance, that in the past the atmosphere was mixed with the icy core of the planet, which is also deuterium-rich.

ISO obtained accurate values of the amount of deuterium in the atmospheres of the gaseous planets and confirmed that the cores of Uranus and Neptune are much larger than the cores of Jupiter and Saturn. For the latter two planets the icy core is so small that it doesn't affect the deuterium abundance in the atmosphere, whilst the larger cores of Uranus and of Neptune have indeed been mixed with their atmospheres and their composition has altered.

Solar genealogy

Comets are another key place to search in the quest to unlock the history of the Solar System. Comets are made of 'pure' protosolar material that, unlike the building material of the planets, has undergone almost no processing. The study of comets can therefore be used to build a 'genealogy' of the Solar System as a whole: the chemical composition of the comets reveals the kind of stars that contributed material to the protosolar nebula.

Just as if they were looking for a precise genetic marker in the members of a family, 'solar-system archeologists' look for chemical compounds that are present both in comets and stars. Clear evidence for such a connection came when ISO detected the crystal olivine, one of the main constituents of the Earth's interior, in Comet Hale-Bopp and in dust clouds surrounding half a dozen aged and dying stars.

Recently, in another experiment, chemists studied a specific type of tiny grain that lurks in interplanetary space and is known to come from comets. The grains were collected from the upper regions of the Earth's atmosphere by balloons. Their chemical composition was compared with that of the grains around stars and, despite their very different origins, found to be very similar. The work is still in progress, but the results already show that the protosolar nebula received dust contributions from many different types of stars.

Saturn Seen in Infrared Light

Hubble/NICMOS

A near-infrared NICMOS image of Saturn. The image gives information about the clouds and haze in Saturn's atmosphere. The blue colours indicate a clear atmosphere above a main cloud layer. Different shades of blue show the variations in composition and size of the cloud particles. The green and yellow colours indicate haze above the main cloud layer. The haze is thin where the colours are green, but thick where they are yellow. The red and orange colours indicate clouds reaching high up into the atmosphere.

Stardust among the planets

Crystals in comets

Surveying Jupiter

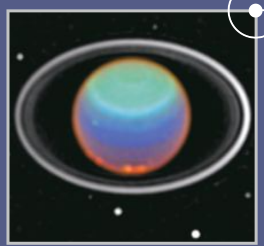
Chemistry of the gaseous planets

Comet Hale-Bopp

Eckhard Slawik

The very bright comet Hale-Bopp (seen here in a ground-based photograph) was studied in detail with ISO. ISO found interesting connections between comets and planets by the detection of specific minerals like olivine.

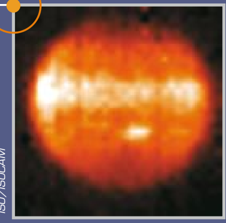
Near-infrared View of Uranus



Hubble/NICMOS

The planet Uranus shows a variety of cloud-bands when viewed in the infrared. The blue colours in this image show the deepest layers. Green shows methane gas and indicates a clear atmosphere. Red shows hydrogen, which is the most abundant gas in Neptune's atmosphere.

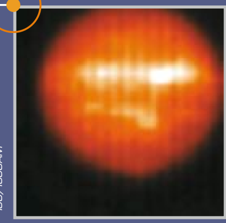
Infrared Jupiter (3 µm)



ISO/ISOCAM

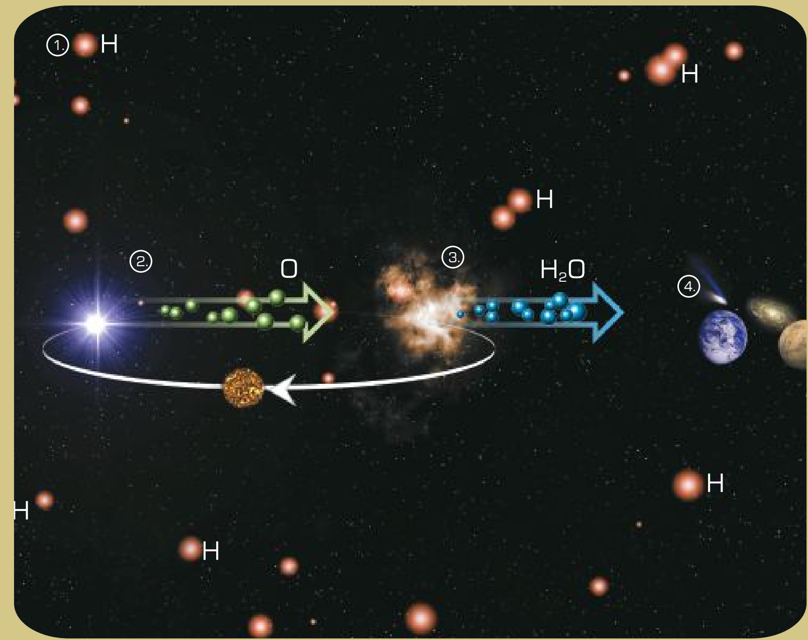
The different views of Jupiter shown in these two images give important information about the chemistry and the 'weather' in Jupiter's atmosphere. At a wavelength of 3 microns the planet appears similar to its familiar visible light image. The bright central band in the image on the left is the Equatorial zone, and below it is the Great Red Spot.

Infrared Jupiter (5.7 µm)



ISO/ISOCAM

At a wavelength of 5.7 microns dry, anti-cyclonic regions of sinking gas appear as bright features in Jupiter's northern hemisphere.



Hydrogen (1.) was originally produced in the Big Bang and is found everywhere in the Universe. Oxygen (2.) is made in stars and dispersed out into the Universe in events such as supernova explosions. The two elements mix in star-forming clouds (3.) and form large amounts of water (H_2O). The molecules of water leave the clouds and end up in many different places (4.) – comets, planets, the centres of galaxies...
When the newly-born stars become old more oxygen is made available to the cosmic water factory.

THE COSMIC WATER FACTORY

Making water is simple. You just need oxygen, twice as much hydrogen and a certain amount of energy. Precisely because of the simplicity of this recipe, most water on Earth was not produced here – it came from space. This is old news for astronomers, but until now water-producing factories had not been observed at work in space. Nor was it possible to trace water at the different stages of its long journey through space. Very little information about cosmic water can be obtained from the ground – primarily because the Earth's atmosphere is itself rich in water vapour and blocks our view of the water in the Universe beyond. Infrared space telescopes have made observations of the cosmic cycle of water possible.

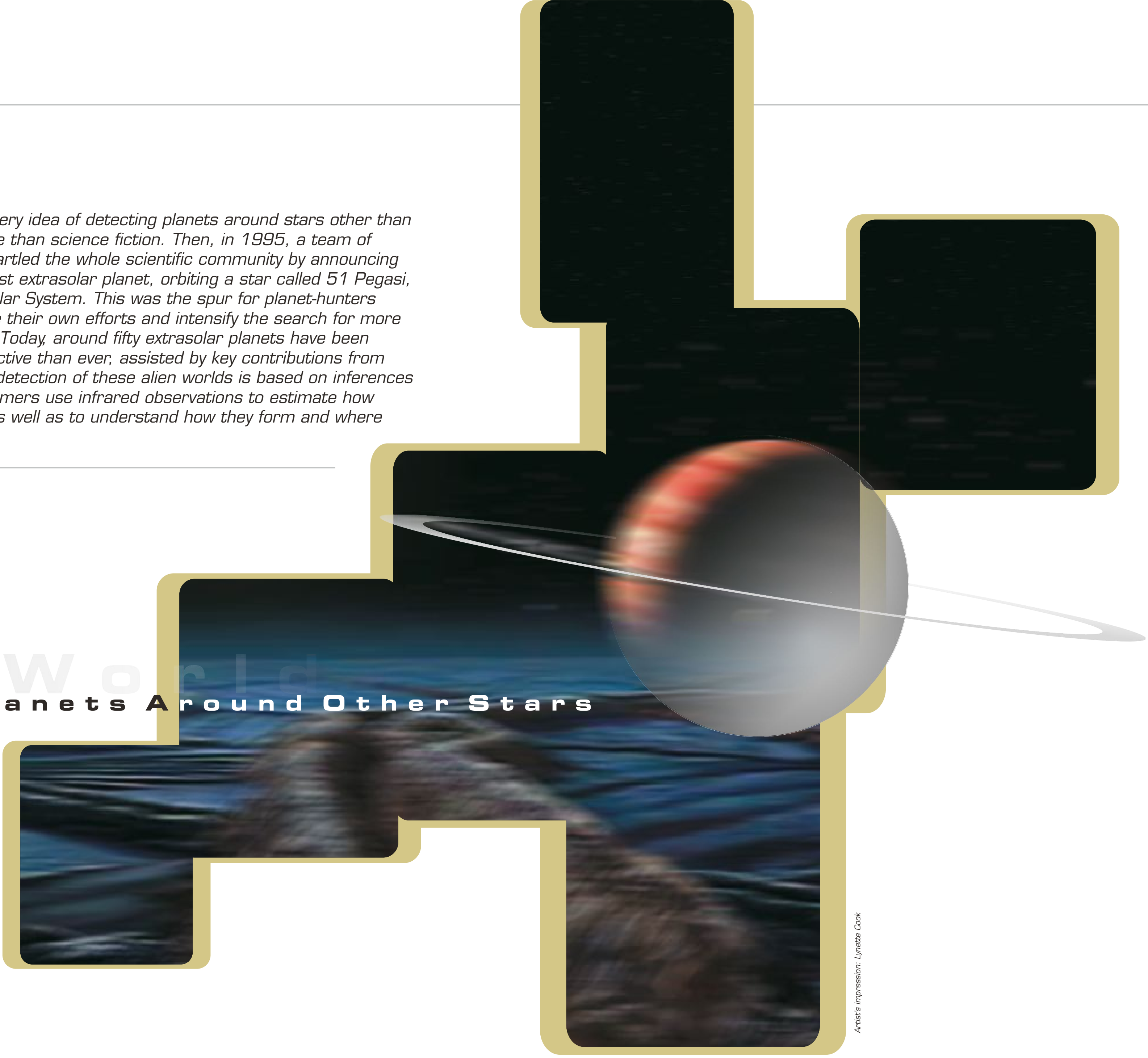
The ingredients of water are plentiful in space. Hydrogen is the most abundant element in the Universe and oxygen is produced at the centres of massive stars and dispersed into space by stellar winds or supernova explosions. For these gases to combine and form water they need to be heated to the kind of temperatures readily found in places such as star-forming regions. When the gas in these regions reaches approximately 130°C, everything is ready to synthesise water.

ESA's ISO succeeded in observing the process. In 1997, in the Orion Nebula, the most studied star-forming region, ISO detected large quantities of water. The delighted astronomers estimated that the water-production rate in the nebula could fill Earth's oceans 60 times a day. Some of the newly formed water molecules start a journey out into the cold of interstellar space, where they form ice grains. ISO has also detected water in many other regions, including the galactic centre and in both newly-born and dying stars.

Alien Worlds

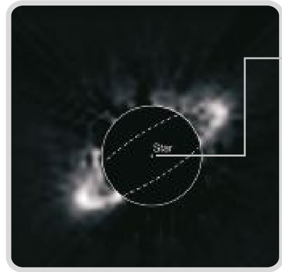
— Planets Around Other Stars

Only a decade ago the very idea of detecting planets around stars other than the Sun was little more than science fiction. Then, in 1995, a team of Swiss astronomers startled the whole scientific community by announcing the discovery of the first extrasolar planet, orbiting a star called 51 Pegasi, located 50 light years from the Solar System. This was the spur for planet-hunters from all over the world to redouble their own efforts and intensify the search for more such planets, with great success. Today, around fifty extrasolar planets have been catalogued and the field is more active than ever, assisted by key contributions from infrared astronomy. Although the detection of these alien worlds is based on inferences from optical observations, astronomers use infrared observations to estimate how common extrasolar planets are, as well as to understand how they form and where they are most likely to be found.



Artist's impression: Lynette Cook

Circumstellar Disc HR 4796A



Hubble/NICMOS

The dust ring seen in the near-infrared image to the left is the left-over material from the formation of the star and possibly a planetary system. The ring was probably created as one or more planets swept up material closer to the central star.

Dust Discs Around Young Stars

Hubble/NICMOS

Near-infrared images of young stellar discs. The dark regions show the areas where planetary systems are likely to be forming. These dusty discs are difficult to image with optical telescopes since the glare from the central star is too intense.

In 1983 the first real infrared space telescope, IRAS, obtained, by pure chance, the first observation of the debris left over from the formation of a planetary system. IRAS astronomers were testing the performance of the telescope by pointing it at a supposedly well-known source, Vega, the fifth brightest star in the sky, in the constellation of Lyra. In addition to the expected light from Vega, IRAS detected radiation from a disc of cool material surrounding the star. This was the first evidence of the existence of the transient cloud of residual material that swirls around a star after planets have formed.

Similar discoveries followed around other Vega-like stars. These are relatively young stars, although they have already reached the most stable stage of their lives, the so-called 'main sequence'. Recently, NICMOS, the infrared camera onboard the Hubble Space Telescope, saw several of these discs in much greater detail than IRAS. Two of them are very far from the central star, at twice the distance from the Sun to Saturn in one case, and six times that distance in the other.

The disc seen by NICMOS around the star HR 4796A, in the constellation of Centaurus, has been reported to have a gap. It is assumed that one or more large planets have swept this part of the disc clear, in the process of accreting material.

The first steps towards a new planet

As soon as the disc around Vega was discovered, it was realised that this disc must be the remnant of a much denser, thicker disc built up earlier, during the process of star-birth. Thicker discs are made of both gas and dust, but most of this material lasts for no longer than a few million years: either it falls into the soon-to-be star or is expelled from the system by powerful stellar winds. When the fully formed young star emerges from the parent nebula, only a thin disc, similar to that around Vega, surrounds it.

By this stage most of the process of planetary formation is already complete. Although the details are still unclear, it appears that while the star is being formed, small, solid particles in the disc called 'planetesimals' collide with each other and grow into larger bodies. These solid cores attract gas to form planetary atmospheres and incidentally remove material from the disc. Thin discs such as that around Vega are made of residual material that has not been swept up by either the central star or the newly formed planets or dispersed by stellar winds, although these processes continue and the disc should eventually disappear.

Optical telescopes can see the thicker discs, where planetary formation starts. Some become visible in silhouette in front of the bright glow of star-forming regions. The Hubble Space Telescope has imaged several of them as small black discs dotted across the face of the Orion Nebula, a famous star nursery. However, the thinner discs that are left after planets have formed can only be observed in the infrared, as in the case of Vega.

Astronomers have tried to find other examples of thin discs, to determine how common they are. A broad study with ISO of 84 main-sequence stars of different ages, including stars like Vega, has produced several key results. It appears that almost all young stars have a thin disc, but, in stars above a certain age, the discs have been swept away by planets and have thus disappeared. This suggests that, not only are discs a common phenomenon, but also, that extrasolar planets are not unusual.

Bombarded Planets

ISO found the critical age dividing stars with and without thin discs to be around 400 million years. Most stars younger than this have discs; most older stars do not. How does this apply to our own Solar System? When the Solar System was young, the newly-born planets scattered the remaining planetesimals, which were then either ejected from the system or attracted by the Sun or other large bodies. The Moon, for instance, suffered many collisions during this phase, according to age determinations of lunar rocks brought back by the Apollo missions.

Harm Habing (Leiden University, The Netherlands) explains: "*In our Solar System, the disc orbiting the Sun disappeared very soon after the formation of the planets. Evidence for this is provided by lunar craters, which were made by comet impacts when the Sun was 300 to 400 million years old. At this time the planets were almost fully formed and the Sun was losing its disc of debris*".

Scientists postulate that the young stars in the ISO sample are probably surrounded by planets undergoing a similar phase of heavy bombardment. When this process finishes, presumably shortly after their 400 millionth birthdays, their discs will also have disappeared.

Although our Solar System was formed about 5 billion years ago, some traces of the formation process itself still remain. This image shows the zodiacal light (the triangle to the right), which is created when sunlight is reflected by dust particles orbiting in the plane of the Ecliptic in our Solar System. Some of these dust particles are remnants from the period when the Solar System formed.

Akira Fuji

IRAS

The IRAS image to the left shows dust and gas signatures in the constellation of Orion. Some of these interstellar dust clouds are known as 'cirrus'. This name emphasises the similarity with the well-known ragged clouds often seen in terrestrial summer skies.

DUST: CRYSTALLINE SILICATES

Dust is the most abundant raw material in the Universe. Planets, asteroids, comets… they are all made from reprocessed dust. There is a perfect 'dust-cycle' taking place in the Universe: stars expel dust when they are old, the dust forms dense clouds in interstellar space and new stars – and often planetary systems – are formed from the dust in that cloud. When the new stars become old and expel dust themselves the cycle closes (although the dust will be more processed and therefore have a slightly different chemical composition).

The dust is opaque to optical telescopes, but becomes transparent when observed in the infrared. Infrared space telescopes have enabled a much better understanding of the chemical composition of dust and this, in turn, has yielded a wonderful by-product: astronomers can now 'trace' the dust through the different stages of its cycle.

One of the most celebrated recent infrared findings is that crystallised silicates - such as olivine - are the main component of dust. The discovery has triggered a 'crystalline revolution' in the astronomical world. Silicates are the most abundant minerals on Earth and are also known to be very common in space. However, it had been assumed that cosmic dust silicates had, in general, an amorphous, disordered structure until ESA's ISO detected them as crystals in many different environments. "There are many different kinds of silicates and the fact that their structure is crystalline and not amorphous allows us to identify them", explains Dutch astronomer Rens Waters (Amsterdam University). "It's really fantastic – we can track the presence of different silicates in different regions and follow their journey through space."

So far crystalline silicates have been found in the circumstellar discs around evolved stars, in comets, and in protoplanetary discs. Experts in space chemistry still do not understand how crystalline silicates are formed, but they can already celebrate the birth of a new field of research – 'astro-mineralogy'.

Background: Simulation by Geoff Bryden

A Planet in the Making Cleans Up

Simulation: Pawel Artymowicz

A computer simulation of how a Jupiter-sized planet would sweep up dust and gas from a circumstellar disc in the formation process. A similar computer simulation in 3D is shown as the background to this page.

Dust Disc in the Orion Nebula

Hubble/NICMOS

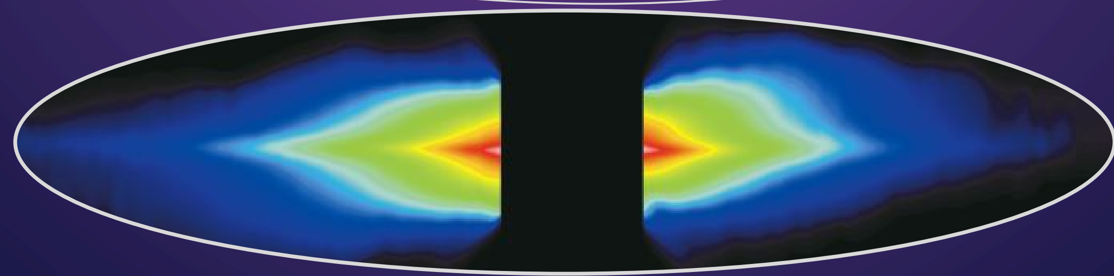
A near-infrared image of a planetary system forming in the Orion Nebula.

Proplyd in the Orion Nebula

Hubble/WFPC2

An image in visible light of a so-called protoplanetary disc, or proplyd, in Orion. The bright light from the nebula behind makes it possible in this unique case to see the proplyds directly with optical telescopes.

Dust Disc Around Beta Pictoris



Hubble/WFPC2

Based on the results from IRAS, optical telescopes were pointed towards Vega-like stars, and, as is the case with Beta Pictoris shown here, discs of debris were found. Beta Pictoris was one of the first such discs to be found, and clearly shows how our own Solar System could have looked 5 billion years ago to an outside observer.

The life of a star follows a familiar pattern, in that it is born, grows and eventually dies. New stars arise from material ejected by previous generations of stars. The lifetime of a star depends on its mass and varies from a few million years to more than the present age of the Universe, which is more than 10 billion years. Today, astronomers have a clear picture of stellar life between infancy and old age, but the beginning and end of a star's life are still somewhat mysterious, dust-shrouded events. Infrared telescopes have been crucial in unravelling these hidden chapters of stellar life. Infrared radiation, unlike visible light, can pass through dust, so infrared observations can probe behind the enveloping dust to fill out the hidden details of these missing years.

Stars form within dense clouds of dust and gas. At some point the material in the clouds starts to collapse, forming a spinning core surrounded by a flattened disc. After a few million years the star begins to shine when nuclear reactions in the core start to convert the constituent hydrogen into helium. These reactions continue through much of a star's life and produce huge amounts of energy to keep the star shining. The dust cloud around the newly-born star thins gradually and the star is revealed to the outside world.

Cataloguing the stellar nursery

An early survey by IRAS detected large numbers of young stars, invisible to optical telescopes. ISO has extended this work, using its camera, ISOCAM, to make a complete census of 'baby stars' in nearby star-forming regions. One such region is the Rho Ophiuchi cloud, at a distance of about 4,500 light years, where around 120 young stars are now known to be hidden, twice as many as known from previous surveys.

ISO has also made the first images of the youngest of all stars, so-called 'pre-stellar' cores. The first examples of these were discovered by radio telescopes only a decade ago and ISO has now catalogued a dozen of them. They are very cold objects – about -260°C – and are thought to be very young protostars that have just started to accrete gas within the cloud.

These extended catalogues of young stars and pre-stellar cores should be of great help in understanding the process of star-birth. As Christoffel Waelkens (Instituut voor Sterrenkunde, Belgium) says in the book "Century of Space Science": *"From the richness of the results it can be anticipated that the ISO database will be a major source for further observations with powerful ground-based instruments. The ISO legacy will serve as a guideline for larger, future space projects."*

Star-forming Region OMC-1 in Orion

Hubble/NICMOS

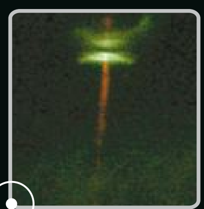
Hubble's high-resolution infrared vision reveals a chaotic, active star birth region. Here, stars and glowing interstellar dust, heated by the intense starlight, appear yellow-orange. Some details are as small as the size of our Solar System.

The Horsehead Nebula

ISO/ISOCAM

ISO image at 7 and 15 microns. Much of the bright infrared radiation comes from carbon compounds (PAHs).

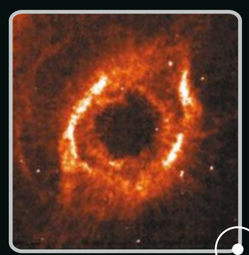
Young Star



Hubble/WFPC2

The object known as Herbig-Haro 30 is a very young star surrounded by a thin dusty disc that blocks the light. Gaseous jets (red) are emitted from both poles. They are formed by infall of material onto the star.

The Helix Nebula



ISO/ISOCAM

ISO 6.75 micron image of the Helix Planetary Nebula, the shroud of a dying star.

ISO/ISOCAM

The Rho Ophiuchi Cloud

ISO colour image taken at 6.75 and 15 microns. The scattered bright dots are newly-born stars.

SPYING ON THE LIFE OF STARS

Failed stars

In star-forming regions there are also objects that failed to gather enough material from the surrounding cloud to start to shine. These objects are called brown dwarfs and, because of the surrounding dust cloud and their low temperature, it is very difficult to see them with optical telescopes. NICMOS, the infrared camera onboard the Hubble Space Telescope, has recently uncovered a swarm of newly-born brown dwarfs throughout the Orion Nebula's Trapezium cluster, about 1,500 light-years from Earth.

Although brown dwarfs are not spectacular, astronomers are eager to know how many exist in our Galaxy. If they were very numerous, they could contribute a significant fraction of the total mass of the Galaxy, which would have important consequences for our understanding of the Milky Way. From studies such as those carried out by ISO, it appears that brown dwarfs do indeed exist, but that they do not dominate the mass budget of our galaxy.

Old stars, vast chemical factories

The other largely unexplored chapter in the lifecycle of a star is the last – old age and death. A star is old when all the hydrogen in its core has been converted into helium. It then begins to burn the helium, converting it into other chemical elements and heralding other important changes.

In an intermediate-mass star like the Sun, the interior regions contract and heat up, while the outer parts expand and cool. The star becomes a red giant, a very large and relatively cool star with a small core. Soon the expanded layers start to lose dust, which forms a thin shell enclosing the diminished star. The shell continues to grow and in time will become a beautiful object called a planetary nebula. The whole transformation from red giant to planetary nebula takes only a few tens of thousands of years – a blink of an eye in astronomical terms.

Chemical elements released by the star begin to combine in the dust shell surrounding it. The shell is a complex mix of simple molecules and ices and more complex molecules and grains. Many of the compounds present in these shells have not been identified, nor are many of the chemical reactions taking place well understood.

Recent observations with infrared spectrographs, such as those onboard ISO, are able to identify a whole new variety of compounds and interactions.

The Egg Nebula (infrared view)

Hubble/NICMOS

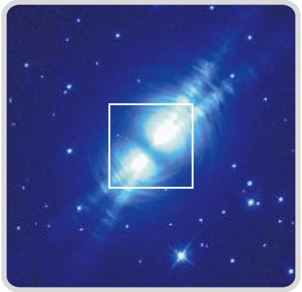
The planetary nebula called the Egg Nebula seen in near-infrared light. Blue corresponds to starlight reflected by dust particles, and red corresponds to heat radiation emitted by warm hydrogen. By comparing it with the optical image below, it can be seen with stunning clarity how the infrared perspective can reveal entirely new processes.

To identify a compound from space, astrochemists compare its spectrum with that of known material in the laboratory. The spectrum of a compound is unique to it and can be thought of as its signature.

Pedro Garc a Lario (ISO Data Centre, Villafranca, Spain) has studied the results of ISO's survey of 350 dying stars. "*ISO's large database of spectral observations of these stars gives us a much more complete picture of the molecules formed in their outer atmospheres, as well as of the dust grains present in the circumstellar envelopes.*"

The solid particles in a star's circumstellar shell are mostly silicates, oxides and carbonaceous material. The existence of crystalline silicates (see box on page 20) has been one of the surprise discoveries of the ISO mission and has opened up a completely new field of research. Most of the carbon in the Universe is manufactured by nuclear reactions in the cores of red giant stars, providing a huge reservoir of base materials for the rich carbon-based chemistry revealed by ISO. Carbonaceous compounds found by ISO include the so-called polycyclic aromatic hydrocarbons (PAHs – see box on page 29), and possibly microscopic diamonds and so-called fullerenes or 'buckyballs' – tiny molecular cages of more than sixty carbon atoms.

The Egg Nebula (visible view)



Hubble/WFPC2

A view in visible light of the Egg Nebula, shown above in infrared. A dust disc blocking the view to the 'waist' of the star is seen in the image to the right. The infrared image (above) penetrates through most of the dust, and reveals a thick disc of warm gas there.

Complicated Jet from Young Star

Hubble/WFPC2

This young star shows that star-formation is by no means a simple process. The star (hidden in the cloud at lower left) ejects a 5 million km long jet that penetrates the surrounding environment at high speed.

The Rotten Egg Nebula

Hubble/NICMOS

The 'Rotten Egg Nebula', imaged by NICMOS, is an example of a proto-planetary nebula – an object which is in the transition phase between a red giant star and a planetary nebula. A direct view of the central star is blocked by dust expelled in the red giant phase, but its starlight is reflected from the dust.

Infrared Peek into a Stellar Nursery

Hubble/NICMOS

A swarm of young brown dwarfs in the Orion Nebula is revealed in this near-infrared image. Optical images cannot see through the vast amounts of dust and gas in the nebula, and do not show the low-mass brown dwarfs sprinkled all over this region. The group of bright stars just below the centre of the image is the Trapezium Cluster.

A Close-up of the Centre of Our Galaxy

The Milky Way is a large spiral galaxy about 100,000 light years across. Our Solar System lies at the edge of one of the spiral arms, about 25,000 light years from the galactic centre, which, as seen from Earth, lies in the direction of the constellation of Sagittarius. 25,000 light years is not a large distance, considering that today's telescopes can picture objects located more than 10 billion light years away. But, despite their proximity, the central regions of the Milky Way still hold many mysteries, and infrared astronomy has just started to solve them. In the last decade, infrared space missions have peered into massive young star clusters, exposed the brightest star in the Galaxy and discovered a hundred thousand stars never seen before.

The Milky Way is shaped like a thin disc with spiral arms and a great bulge in the centre. Light from the centre of our Galaxy has to pass through a huge amount of dust and gas that hinders and partially blocks its path to the Earth. However, not all types of light are equally affected: infrared light manages to dodge the obstacles much more successfully than visible light. So, with the relatively recent arrival of infrared telescopes, astronomers are only now beginning to obtain detailed views of the centre of the Galaxy with dramatic results.

In 1997, the infrared camera onboard the Hubble Space Telescope, NICMOS, obtained very clear images of the largest young clusters of stars yet found in the Galaxy: the Arches and Quintuplet clusters. Located less than 100 light years from the very centre of the Galaxy, they are ten times larger than typical young star clusters. They are very dense and just a few million years old, but, despite this, they are unlikely to survive much longer as the immense gravitational forces at the core of the Galaxy will rip them apart in just a few million years. However, until then, they will shine more intensely than any other star cluster in the Galaxy.

For some reason the formation of super-massive stars seems to be favoured in these young clusters. The Arches cluster hosts what could be the most massive, and the brightest star in the Galaxy, the Pistol Star. NICMOS images of this star have revealed an amazing 'monster star' that, for optical telescopes, is completely obscured by the intervening dust. The Pistol Star spans the diameter of the Earth's orbit and spews out as much energy in six seconds as the Sun does in one year. It may have started with about 200 solar masses, but is now rapidly losing material and can be expected to end as a brilliant supernova in between one and three million years. Only ten percent of the infrared light leaving the Pistol Star makes its way through the obscuring dust, but this is enough to put it within reach of modern infrared telescopes.

MILKY WAY

200 BILLION NEIGHBOURING STARS

COBE/DIRBE

The Quintuplet Cluster (below), a massive star cluster near the centre of the Milky Way. It is the home of one of the brightest stars in our Galaxy, the Pistol Star.

Hubble/NICMOS

On dark nights the Milky Way can be seen as a luminous band spanning the entire sky. This band is made up of about 200 billion stars and, together with thousands of nebulae and clusters, constitutes our Galaxy. There is, however, a hidden side to the Milky Way that does not shine at all: the so-called dark matter. Dark matter cannot be detected directly by any instruments.

Obviously it has so far been impossible to obtain any image of our Galaxy from outside, but observations, like the one above made by COBE (Cosmic Microwave Background Explorer), have shown that the Galaxy is shaped like a thin disc with four spiral arms and a bulge in the centre. This bulge includes the galactic centre, the centre of mass of our Galaxy, about which everything in the Milky Way orbits. There is also a huge round halo, a diffuse spherical region surrounding the disc. The stars within the disc tend to be young, while the halo contains older stars. It is believed that this halo is composed mostly of dark matter. This has been deduced from observations of the motion of the spiral arms. Their motion can only be accounted for by including the gravitational attraction of large amounts of dark matter.

A crowded place

ESA's ISO also carried out a deep exploration of the central regions of the Galaxy. One of ISO's longest observing programmes, ISOGAL, devoted 255 hours to observations of stellar populations in the galactic centre, focusing especially on the inner part of the central bulge. This is the most crowded place in the Galaxy, as Alain Omont (Institut d'Astrophysique de Paris) explains: "*The inner bulge is like the centre of a very busy metropolis. The density of stars is 500 times greater than any other place in the galaxy – stars can even bump into each other! These huge populations of stars can give us a lot of information about the whole galaxy*".

ISO identified a previously unknown population of more than 100,000 stars of the 'red giant' type – stars at a late stage of evolution – in a relatively small region of the inner bulge. Most of these stars are so-called 'AGB' stars, which are particularly valuable for astronomers for two reasons. They expel huge amounts of dust out into their surroundings during a brief stage of their lives and are one of the main 'dust-producers' of the Galaxy. Additionally, they provide key clues to the history of star-formation in the Milky Way, as their masses vary according to their age, and so it is possible to determine how long ago a certain population of AGB stars was born.

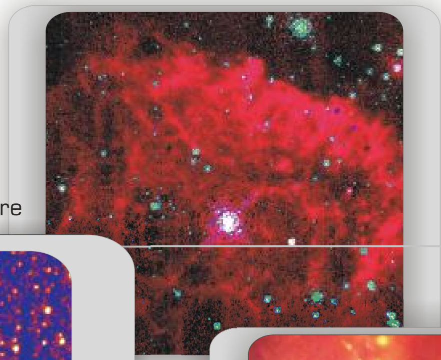
Results from the ISOGAL programme will also help to clarify how the Milky Way itself was formed. As an example, it is thought that our galaxy grew by 'swallowing' dwarf galaxies attracted to it by its gravitational force. Stellar motions are especially hectic at the centre of the galaxy, and by measuring them astronomers will probably be able to trace the stars' origin. Stars coming from a galaxy devoured by the Milky Way in the past are expected to move in a different way from their companions from the original Milky Way itself.

Infrared View of the Centre of Our Milky Way

2Mass/MSX

An infrared view of the centre of our Milky Way. This image is a combination of observations performed by the Two Micron All Sky Survey (2MASS) ground-based project and The Midcourse Space Experiment (MSX) satellite. The colours correspond to: blue, 1.25 μm, green, 2.17 μm and red, 6 - 11 μm. In this image the bulk of the light comes from the very large number of cooler stars seen toward this region. The image gives us a glimpse of the wealth of stars and gas that comprise the very centre of the Milky Way.

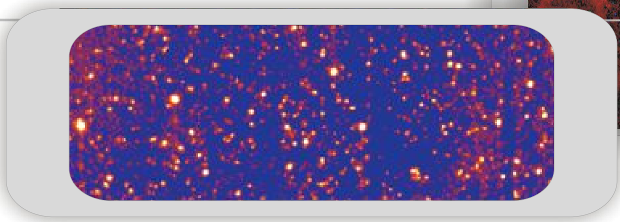
The Pistol Star



Hubble/NICMOS

Hidden completely from view for optical telescopes, the Pistol Star shows up in near-infrared images. This amazing 'monster star' could be the most massive and brightest star in the Galaxy.

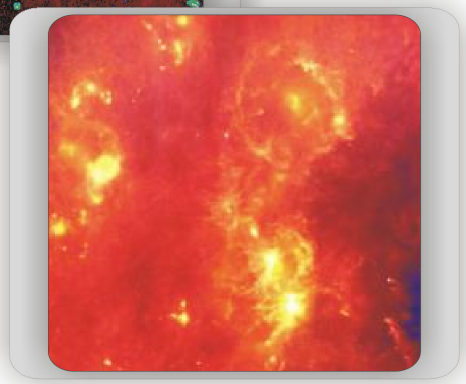
Newly Discovered Stars at the Milky Way's Centre



ISO/ISOCAM

Infrared image of a region at the centre of the Milky Way. It shows some of the more than 100,000 stars discovered by ISO at the galactic centre.

Dust and Gas in The Orion Region



IRAS

This, by now famous, IRAS image shows most of the constellation of Orion. Immense regions of cool dust and gas are seen. The dust and gas are closely related to the active star-formation taking place in the region. The brightest area below the middle is the Orion Nebula. The ring-like structure to the upper right is a remnant from a supernova explosion.

The Infrared Faces of Galaxies

Infrared telescopes can look beyond the dust clouds that obscure the view for conventional optical telescopes and have revealed many surprises, ranging from hidden star-forming regions in nearby galaxies to a remote population of very luminous galaxies.

The Andromeda galaxy, at a mere two and a half million light years away, is one of our closest and best-known neighbours. It is an amazingly beautiful spiral galaxy, ranking very high on the 'hitlists' of many sky-lovers, and is also a striking example of the kind of magical tricks that infrared telescopes can perform. Viewed in the infrared, the Andromeda galaxy loses its spiral arms and appears as a ringed galaxy, with multiple concentric ring-like structures.

The explanation for the ring pattern in the Andromeda galaxy, as seen by IRAS and ISO, lies hidden in the dust that makes up the rings. The temperature of the dust is a chilly -260°C, so there is no bright glow that optical telescopes can detect, although the dust shines brightly in infrared light. The presence of dust is a telltale sign of star formation, and indeed many new stars are being born in the brightest of Andromeda's rings. One of the astronomers who observed the galaxy with ISO, Martin Haas (Max-Planck Institut f r Astronomie in Heidelberg, Germany), predicts: "*So many new stars are being born in the rings of Andromeda, that these rings may also be visible to optical telescopes in the far future.*"

A similar case of star formation regions hidden by intervening dust is observed in the most famous pair of colliding galaxies, the Antennae galaxies, named after their distinctive long, diffuse tails. These tails are clearly seen in optical images and are formed from material ejected as a result of gravitational interaction during the collision. This is, however, only half the story, as galactic collisions compress gas and dust into small regions and create the perfect breeding ground for new stars. That these star-forming regions existed could be deduced from the presence of dust clouds, but the intervening dust itself hides many of the most active star-forming regions from optical telescopes. In the Antennae galaxies, these previously suspected, but unobserved, hidden star-forming regions, were only found when observations from ISO could probe behind the veil of dust.

A black hole's lunch

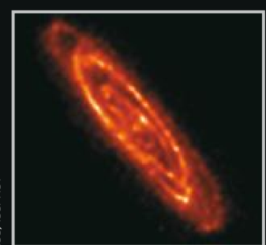
The Antennae galaxies are a wonderful example of two interacting galaxies, but they are not unusual – collisions and even 'cannibalism' are common forms of galactic relationships. At present our own Galaxy is strongly attracting smaller neighbouring galaxies, including the two Magellanic Clouds, and is likely to collide with the Andromeda galaxy within the next thousand million years.

Not surprisingly, these events have strong implications for the fate of the galaxies involved. If two large spiral galaxies such as our own Milky Way and the Andromeda galaxy collide, then the result will probably be a larger elliptical galaxy with no spiral structure, forming several billion years after the original collision. However, if the sizes of the merging galaxies differ considerably, then the larger galaxy will devour the smaller one. ISO and NICMOS found just such a case when observations revealed a 'swallowed' galaxy at the centre of the galaxy Centaurus A.

Centaurus A, or 'Cen A', is a giant elliptical galaxy located only 10 million light-years away. It has an 'Active Galactic Nucleus' (AGN) – a black hole with a mass close to one billion times the mass of our Sun at its centre, which makes the galaxy very luminous. Centaurus A is the closest example of an AGN to our Galaxy. Both ISO and NICMOS peered into the dusty centre of Centaurus A, uncovering the remains of a spiral galaxy 'devoured' by Cen A in the past. The gas from the spiral galaxy is being funnelled into the supermassive black hole at the galactic centre as fuel. The new data from infrared telescopes should help to unravel the 'inside story' of other galaxies with black holes. Already now there are clear indications from NICMOS observations that most, or even all, galaxies host black holes at their centres.

Monsters or babies?

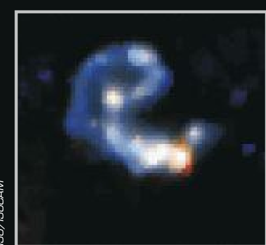
Infrared telescopes have also made discoveries far beyond our local group of galaxies. One of the most celebrated discoveries was made back in the eighties by the pioneering infrared space



ISO/ISOPHOT

ISO image revealing the Andromeda galaxy's ringed structure invisible to optical telescopes. The rings of this galaxy show up in the infrared because they are made of very cold dust.

Dust Rings in the Andromeda Galaxy



ISO/ISOCAM

Infrared image of the Antennae, a pair of galaxies undergoing a collision. The regions where new stars are being born stand out more clearly in the infrared.

The Antennae Galaxies

telescope, IRAS. The observations revealed hundreds of very bright, remote galaxies across the sky that are barely visible to optical telescopes. These objects emit as much as 99 percent of their light in the infrared – a completely new astronomical phenomenon. These mysterious galaxies were named 'Ultra Luminous InfraRed Galaxies', or simply 'ULIRGs'.

As Dieter Lutz (Max Planck Institut f r Extraterrestrische Physik, Garching, Germany) says, "*there were earlier indications that some galaxies emit most of their energy in the infrared. The surprise came when IRAS found how large and widespread the effect is. ULIRGs turned out to be more numerous than quasars* (very distant and bright objects) *of the same luminosity, which were the only objects of very high luminosity known before.*"

A few years later it became clear that each ULIRG is actually a pair of interacting galaxies, although the mechanisms producing the long-lived high luminosity were still not fully understood. The recent discoveries in the Antennae galaxies and Cen-A are examples found relatively nearby of the two main processes by which a galaxy can remain highly luminous for a long time. Could the birth of new stars, as in the case of the Antennae galaxies, or a powerful black hole like that in Cen-A be the cause of the high luminosity in the distant ULIRGs?

The question was finally resolved by ISO. A team led by Lutz and Reinhard Genzel (Max Planck Institut f r Extraterrestrische Physik, Garching, Germany) selected a large sample of ULIRGs and devised a clever method to discriminate between the 'baby stars' and 'black hole monsters' scenarios. Radiation from these processes leaves a characteristic trace in certain gases and determines the survival of soot-like molecules that are abundant in many regions of the Universe, including ULIRGs. ISO spectrometers traced these changes and the results showed that most ULIRGs derive the bulk of their energy from enormous bursts of star-formation, while only a fraction – usually the most luminous ones – are powered by massive black holes in AGNs.

Arp 220 - a ULIRG

Arp 220 is a nearby example of an ultraluminous infrared galaxy. This near-infrared image reveals the two colliding spiral galaxies at the centre of Arp 220, which are the main cause of the bright infrared radiation. The fantastic knots of newly-born stars visible as the bright spots in the image are a result of this spiral collision. The bright knot to the left is the centre of the other broken spiral galaxy.

THE ISO ARCHIVE: THE INFRARED SKY ON THE INTERNET

Cyberspace is increasingly breaking the frontiers of space and time… in the most universal sense. Astronomers have opened quick shortcuts on the Internet leading to the most distant places in the Universe, simply by allowing free access through the web to the images and data gathered by powerful telescopes. Light that has travelled for many billions of years is now at your fingertips. A fast-growing number of researchers are currently using this new resource and are making valuable 'archival discoveries'.

ESA's ISO Archive stores the outcome of the most complete exploration of the infrared Universe so far. ISO was in operation until May 1998 and its database, with nearly 30,000 scientific observations, is situated at the ISO Data Centre in Villafranca, Spain. The ISO Archive went online in December 1998 and is freely accessible at www.iso.vilspa.esa.es

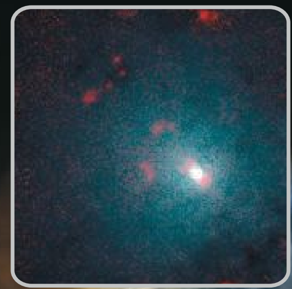
The ISO Archive has become a reference point for astronomers of all kinds, who want to know 'what the infrared has to say' about their favourite object.

Archive Scientist Timo Prusti (ESA) is sure that "the community is benefiting enormously from our archive. The number of observations being retrieved has been constant at 3,000 every month. This shows that astronomers from all over the world are focusing on finding new uses for the ISO archive material, even though new observations are no longer being added."
Apart from the ISO Data Centre at Villafranca there are six National Data Centres: in Groningen (The Netherlands); Garching and Heidelberg (Germany); Orsay-Saclay (France); Rutherford (UK); and Pasadena (California, US).

Centre of Centaurus A (visible light)

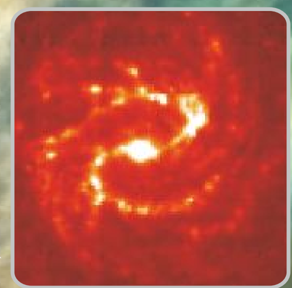
Seen in visible light Centaurus A is a maelstrom of dust, gas, and new and old stars. The chaotic appearance of this galaxy is largely due to the remnants of a smaller spiral galaxy that in the past merged with the original larger elliptical galaxy.

Centre of Centaurus A (infrared light)



A near-infrared image peers past the dust in Centaurus A to discover the swallowed galaxy at its centre.

PAHs in M83



The spiral arms of Messier 83 that contain the star forming regions are very prominent due to emission from dust and from Polycyclic Aromatic Hydrocarbon (PAH) molecules.

Spiral Galaxy Seen in Infrared

NGC 5653 seen in near-infrared. Red corresponds to glowing hydrogen, the raw material for star birth. Many of the red star-forming regions shown here cannot be seen by optical telescopes as they are hidden from view by clouds of gas and dust.

PAHs – UNIDENTIFIED MOLECULES IN SPACE

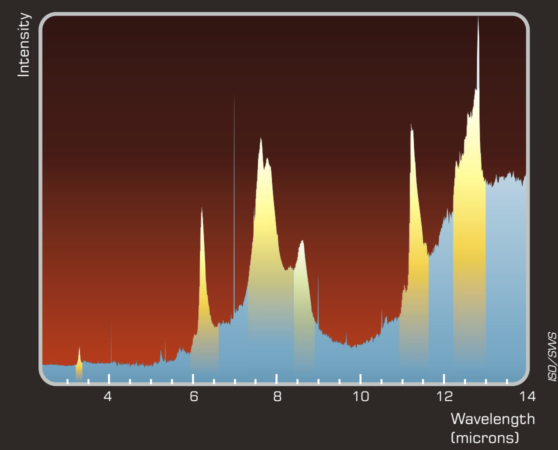
Infrared space missions have been very successful in decoding the chemistry of the Universe. A wealth of molecules has been detected in space by ISO, both in gaseous and solid form, including water, ices and crystalline silicates. The 'chemical signatures' – spectra – of these compounds are collected by spectrographs and then compared with those of standard molecules in the laboratory.

Sometimes the measured spectra do not match up with anything known on Earth and then the identification process becomes much more difficult. This is the case with one of the most ubiquitous classes of molecules so far detected, a compound that leaves its fingerprint throughout our own and many other galaxies.

ISO demonstrated its presence in many different environments. Although the molecules are thought to be carbon-based, no positive identification has been made. More cautious scientists call them simply 'Unidentified Infrared Bands', while for others they are clearly 'PAHs', short for Polycyclic Aromatic Hydrocarbons: large molecules made up of several tens or hundreds of carbon atoms linked together in a ring-like structure.

The very abundance of these molecules shows that a very rich and active organic chemistry exists in the space between and around the stars. Currently comets and meteorites are being searched for links between this remote chemistry and the one evolved in newly-born planetary systems and in our own Solar System.

The spectrum below (blue) is from the starburst galaxy M82, and shows a number of prominent PAH features (coloured yellow).



Who has not dreamt of travelling back in time to solve all those unanswerable questions that history leaves behind? Telescopes can do just that – in a way.. They are a kind of time machine that looks back into the past, to remote parts of the Universe, and takes a snapshot of an instant of the young Universe. The Universe is so large that light can take a long time to travel from one region to another. As a result, light arriving here on Earth from a galaxy ten billion light years away shows us that galaxy as it was in a remote past – ten billion years ago.

Of course, any time traveller would want to seek out the most exciting events of the past and astronomers are no different. They want to observe the very first galaxies and to discover how they formed. Did all galaxies form at much the same time or was it a more gradual process, in which primeval, small galaxies merged to form larger ones? Observations from infrared telescopes have made key contributions in the search for answers to these questions.

Infrared space telescopes have looked back in time to the epoch when galaxies were young. Their revolutionary findings have completely revised the picture built up by observations from optical telescopes. Powerful optical telescopes made the first measurements of distant galaxies, seeing these objects as they were a very long time ago. These observations were then used to estimate the rate at which new stars were formed in the young Universe – a key parameter in determining how galaxies formed. However, when ISO saw the young Universe with infrared eyes, astronomers realised that all previous estimates about star-formation were far too low.

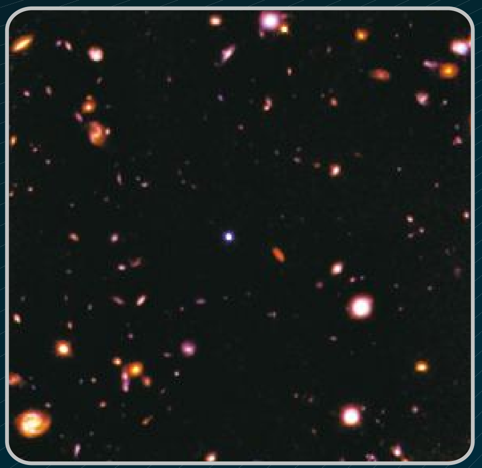
ISO ran several long observing programmes called ‘ISO Deep Surveys’ to study the young Universe. It observed more than a thousand distant, young galaxies where many new stars were being born. The star-formation process is shrouded in dust and it was precisely this dust that had been blocking the view of the optical telescopes and misleading astronomers in their estimations. It could now be concluded that young galaxies formed three to four times more stars than suggested by optical surveys. The distance of the newly observed galaxies corresponded to a time when the Universe was about two-thirds its present age – about ten billion years ago. The ISO observations created great excitement and revealed a young Universe that was much more violent than expected.

Galaxies were evolving very quickly and many new stars were being born. *“We have definitively found a population of luminous star-bursting galaxies, with several times more stars being formed than the rate inferred originally from the optical surveys”*, stated British astronomer Michael Rowan-Robinson (Imperial College, London, UK), when the first results were published in 1998.

The high-resolution NICMOS instrument on the Hubble Space Telescope has also carried out a number of ‘Deep Survey’ observing campaigns. NICMOS was pointed at the so-called ‘Hubble Deep Field North’ for 200 successive hours. This is a region of the sky in which the Hubble Space Telescope had previously observed thousands of very distant galaxies in the visible. NICMOS complemented this with clear images of the most distant galaxies ever seen in the infrared, some of them not observed previously and some up to 12 billion light years away. The NICMOS results, although performed in the near-infrared region, have lent support to ISO surveys performed at longer wavelengths.

NICMOS Deep Field Observation

Hubble/NICMOS

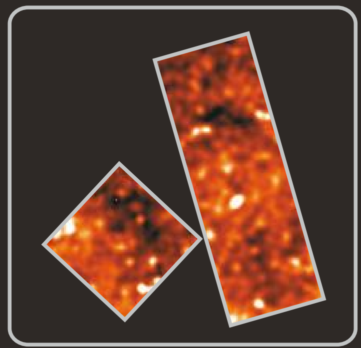


The famous Hubble Deep Field North is here seen in near-infrared through the eyes of Hubble’s NICMOS camera. This image shows some of the most distant galaxies known and was the result of 200 hours of continous observation.

Wall to Wall with Galaxies

Another way to approach the problem of galaxy formation and evolution is to study the ‘infrared background radiation’ of the Universe, a faint relic of the era when the first galaxies emerged. The infrared background radiation is a glow that fills the whole Universe – a kind of ‘wallpaper’ of light, whose existence was predicted three decades ago. It is a remnant of the emission by the dust heated in the star-formation events of the first galaxies. NASA’s COBE satellite detected this ‘infrared wallpaper’ in 1996. As a result of this astronomers now know the amount of light emitted by primeval galaxies and can take a guess at the nature of these objects. Furthermore, with appropriate telescopes they can even hope to observe these galaxies and indeed, a large international consortium called FIRBACK (Far InfraRed Background), working with ISO, has succeeded in discovering the first, very young, actively evolving galaxies that in the past helped to create the infrared background. These results strongly support the ISO findings, showing that the Universe in the past had much more star-formation, and hence active galaxy evolution, than previously thought.

However, this is just a first step. Other infrared instruments, such as the sub-millimetre camera SCUBA installed on a ground-based telescope on Hawaii, have lately identified even more dust-enshrouded primeval galaxies and the search continues. The origin of galaxies is still an open question and will be one of the biggest challenges among those inherited by future infrared space missions.



ISO/ISOPHOT

A Deep ISO Survey

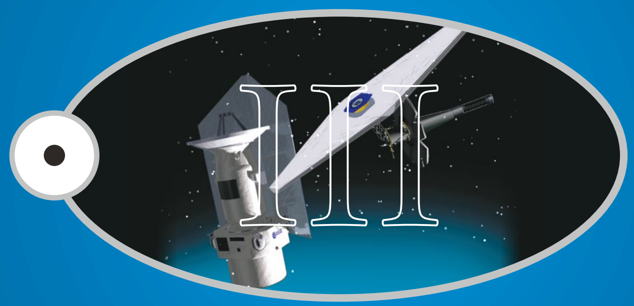
The FIRBACK ISO Deep Survey shows about two dozen distant dusty star-forming galaxies. These are the first individual objects known to contribute their energy to the Cosmic Infrared Background, a radiation that fills the entire Universe like a kind of wallpaper.

COBE/DIRBE

NASA’s COBE satellite delivered valuable information about cosmic microwave radiation, and also mapped the distribution of far-infrared radiation (60-240 microns) on the sky. The dust and gas in our own Milky Way are the most prominent features in this image, but a closer analysis has also revealed a very important component of infrared radiation coming from the distant Universe: the infrared background radiation.

The Infrared Background Radiation

Part III THE FUTURE OF INFRARED ASTRONOMY



The Open Questions

The relatively new science of infrared astronomy has made overwhelming advances in the past decade, but the knowledge gained has also generated many new questions. The list of unsolved problems is long and ranges from studies of planetary systems relatively close to home to surveys of the outer edges of the Universe, looking for the earliest galaxies, formed just after the Big Bang. This section looks at some of the questions that astronomers hope that new infrared studies will resolve in the years to come.

Where and how do planetary systems form and evolve?

Until recently the only planetary system we could study was our own Solar System. Astronomers have now detected indirectly a number of other such systems. Although the planets themselves are difficult to image directly, future infrared space telescopes will enable us to understand how these planetary systems formed and evolved. It is envisaged that future infrared telescopes will carry instruments able to analyse the chemistry at work in the atmospheres of these planets and possibly even to look for traces of living organisms.

How and where do stars form, and what determines their number and their masses?

Stars are the 'witches' cauldrons of the Universe' – they transform the simple light elements into heavier ones and disperse them among the stars. The heavier elements are crucially important for the creation of planets and indeed for life itself. The birth of the first stars triggered a continuing chain of cosmic recycling to which we owe our existence. However the processes by which stars, their surrounding protoplanetary discs and the planets themselves are made remain poorly understood. Observing in the infrared part of the spectrum, future telescopes will be able to penetrate the dusty envelopes around newly-born stars and take a closer look at the stars themselves.

How old are the stars in our Milky Way and its neighbours – and what do these stars tell us of their origin?

The stars in our 'local' Universe – our own galaxy and its near neighbours - represent a fossil record of their evolutionary history. In the future infrared space telescopes will be able to decipher this fossil history for a large number of our neighbouring galaxies, significantly extending the work on our nearest companions started by ISO and Hubble.

When and how did the first stars and galaxies form?

We are on the threshold of being able to see the earliest luminous objects in the Universe. For the first time in human history we will soon be able to investigate the origin of galaxies directly. The term 'dark ages' is used today to describe the epoch close to the beginning of the Universe after the microwave background radiation was emitted, but before stars and galaxies became common. This period lasted some 1-2 billion years, and the first objects to illuminate the darkness glow faintly, far in the infrared, partly hidden by dust and cannot be detected by present-day telescopes.

How large and how old is the Universe and what is its ultimate fate?

Astronomers hope to measure the size and geometric structure of the Universe by using distant infrared supernovae as 'standard candles' of known brightness. These measurements should establish whether the Universe will continue to expand forever. Today we see indications that the expansion is actually accelerating, rather than decelerating under the influence of gravity from its constituent matter.

Some of the future infrared space telescopes (like NGST) will be uniquely powerful tools to study the effects of the mysterious dark matter. We know that this strange form of matter constitutes more than 90% of the mass of the Universe, but cannot observe it directly. Although NGST, like other telescopes, can only observe luminous objects, it will be able to detect subtle distortions in the shapes of the most distant galaxies caused by the gravitational deflections of the intervening mass and so resolve some of the questions surrounding dark matter.

The infrared space telescopes of the future, such as ESA's Herschel Space Observatory, and NASA/ESA/CSA Next Generation Space Telescope (NGST), will tackle these new questions armed with larger mirrors, more sensitive detectors and a wider coverage of the infrared spectrum than any previous space telescopes. They will be in a unique position to make a significant contribution to our understanding of the Universe.

Future Infrared Missions

Infrared Astronomy Timeline, Future

Space

2002 NASA's SIRTF (Space Infrared Telescope Facility) is scheduled for launch in July 2002.

2002 SOFIA (Stratospheric Observatory For Infrared Astronomy) is scheduled to begin operations as a collaboration between NASA and the German Space Agency (DLR).

2004 Launch of ASTRO-F/IRIS (Infrared Imaging Surveyor), a Japanese infrared space mission.

2007 Launch of ESA's Herschel Space Observatory.

2007 Launch of ESA's Planck satellite.

2009 Launch of the NASA/ESA/CSA NGST (Next Generation Space Telescope).

Ground-based

2001 The infrared interferometers connecting the two Keck telescopes are expected to begin operations.

2002 VLTI (Very Large Telescope Interferometry) is expected to begin operations.

2004 Expected completion of the first generation of instruments for the four VLT telescopes (including several IR instruments).

2010 Expected completion of ALMA (Atacama Large Millimeter Array).

Herschel – Looking at the Formation of Stars and Galaxies

In the mid-nineties the Hubble Space Telescope carried out its famous 'Deep Field' programmes and gave astronomers their first clear look back to the time when galaxies were forming. Thousands of galaxies, located more than 10 billion light-years away, were revealed. These galaxies seemed to be smaller and more irregular than those nearby. This gave a valuable clue as to how galaxies might have formed. However, these astonishing images also raised more questions, such as how cosmic dust might have affected the observations. How could astronomers be sure that Hubble was showing a typical group of young galaxies and not only those that could be seen through the obscuring dust? It was clear that only a large space telescope, working at infrared wavelengths and thus able to both see the dust and 'through' the dust, could solve that problem.

Simulated Herschel Observation

Simulation: Dieter Lutz

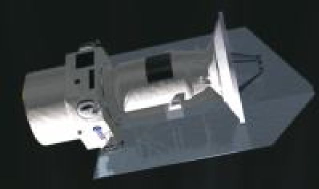
Simulation of how Herschel will detect obscured galaxies in the distant Universe. Blue, green, and red correspond to wavelengths of 75, 110, and 175 microns in the far infrared. The simulation demonstrates Herschel's unique capability to observe very infrared objects with much better detail than previously possible.

ESA's Herschel Space Observatory to be launched in 2007, is capable of making just such observations. Herschel is the first space observatory covering the full far-infrared and submillimetre waveband. By probing so much further into the infrared than any other space telescope, it will have the potential to discover the earliest proto-galaxies and to clarify how they evolved. Herschel's 3.5 metre mirror will also make it the largest telescope to be sent into space.

"Herschel will open a new generation of giant space telescopes, and will be the first instrument able to look very far in space and time without being confused by the dust. Herschel will be a unique facility. We can expect a great deal from it", explains G ran Pilbratt, Herschel Project Scientist.

Although Herschel's major challenge will be to discover how the first stars and galaxies formed, it will also study the chemical processes at work around stars, in the space between them and also in objects in the Solar System.

Herschel will be located 1.5 million kilometres away from Earth, so that it can avoid the strong far-infrared emission from the Earth and the Moon. It will carry three instruments, cameras and spectrographs. These instruments constitute one of the technological hurdles of the mission, as their detectors will have to be kept at a temperature close to absolute zero (-273ºC). The large mirror presents another major challenge. It not only has to be very light, but has to be able to withstand the extreme conditions of the launch and the intense cold of outer space. Furthermore, it must be superbly well polished.



Artist's impression: ESA

Herschel

Dimensions: *Height, 9 metres. Width, 4.5 metres*

Mirror size: *3.5 metres*

Launch: *Herschel will be launched on an Ariane 5 rocket in 2007 together with another ESA scientific mission, Planck. The satellites will separate shortly after launch and will operate independently.*

Launch mass: *3.3 tonnes*

Instruments: *HIFI (Heterodyne Instrument for Herschel), a high-resolution spectrograph; PACS (Photoconductor Array Camera and Spectrometer); SPIRE (Spectral and Photometric Imaging REceiver), a camera and spectrometer*

Wavelength coverage: *60 to 670 microns*

Temperature of instruments: *down to a few tenths of a degree above absolute zero (-273.15°C).*

Operational lifetime: *Minimum 3 years of routine science operations.*

Orbit: *Herschel will orbit a point in space called 'Sun-Earth L2', 1.5 million kilometres away from Earth.*

Collaboration: *Herschel's instruments are being designed and developed by more than 40 institutions, mainly European, organised in three consortia.*

Simulated NGST Observation

Simulation: Myungshin Im

Simulation of a 30 hour exposure with NGST. Blue, green, and red correspond to 0.8, 1.2 and 2.0 microns in the near-infrared. The vast number of galaxies in this simulation demonstrates NGST's ability to observe even the faintest infrared objects.

NGST – Fighting the Expansion of the Universe

As astronomers look out to the edge of the known Universe they are looking back in time, and because the Universe is expanding, light from these remote objects is stretched to longer, redder wavelengths. For the most distant objects the light will be shifted out of the visible region and into the infrared by the time it is received here on Earth. To produce sharp images of the very first objects populating the Universe after the Big Bang an infrared telescope with a large mirror is needed. The Next Generation Space Telescope (NGST), conceived as a successor to the Hubble Space Telescope and due to be launched in 2009 by NASA, ESA and CSA (Canadian Space Agency), is just such a telescope.

NGST will observe at near-infrared wavelengths and has an 6-8-metre primary mirror, capable of gathering five to ten times more light than Hubble, giving a much sharper infrared view and able to detect fainter objects.

"As powerful as the Hubble Space Telescope is, it has only scratched the surface of the young distant Universe. When thinking about Hubble's successor, you can't 'fight the redshift' – if you want to look further back in time you also need to follow the light in wavelength into the infrared", says Peter Jakobsen, ESA's NGST Project Scientist.

The NGST project began in the mid-nineties as a result of a study to define the telescope to come after Hubble. The authors originally proposed a mirror 4-metres in diameter, but later this figure was made larger. Since 1997, NASA, ESA and the CSA have collaborated to define the exact specification of this worthy successor.

There are high scientific expectations for NGST and it should solve many of the key problems troubling infrared astronomy today. But the technological challenges associated with the mission are considerable. For instance, the 6-8-metre telescope mirror has to be packed into a small rocket with a diameter of only about 5 metres. To do this the mirror is made in several parts and folded up like the petals of a flower during launch. The mirror will then be unfolded when the satellite reaches its final destination, the L2 point, 1.5 million kilometres away from Earth. Some of the scientists working on the construction of NGST have described it as "*a bit like designing a ship in a bottle*".

NGST

Dimensions: *Height and width: 10 -15 metres, sunshield approximately 30 metres*

Mirror size: *6-8 metres*

Launch: *NGST will be launched by an unmanned launcher in 2009*

Launch mass: *3 tonnes*

Instruments: *Visible/Near-infrared camera, Near-infrared spectrograph, and a mid-infrared combined camera and spectrograph.*

Wavelength coverage: *0.6 to 28 microns*

Temperature of instruments: *-240°C*

Operational lifetime: *Minimum 5 years of routine science operations*

Orbit: *Sun-Earth L2 (1.5 million km from Earth)*

Collaboration: *NGST is a collaboration between NASA, ESA and CSA (Canadian Space Agency) at foreseen levels of 80%, 15% and 5% respectively.*

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This brochure could never have been produced without help from a number of scientists and institutions:

Alain Abergel
Pawel Artymowicz
Piero Benvenuti
Geoff Bryden
Joris Blommaert
Pierre Cox
Ewine van Dishoeck
Th r se Encrenaz
Helmut Feuchtgruber
Wolfram Freudling
Bob Fosbury
Pedro Garc a Lario
Martin Harwit
Richard Hook
Infrared Processing and Analysis Center
ISO Data Centre
Peter Jakobsen
Martin Kessler
Rene Laureijs
Michael Linden-Vørnle
Dieter Lutz
Leo Metcalfe
Felix Mirabel
Alan Moorwood
Francisco Najarro
G ran Pilbratt
Alberto Salama
SIRTF Science Center
Space Telescope-European Coordinating Facility (ST-ECF)
Henrik Spoon
Christoffel Waelkens