herschel

→ SCIENCE AND LEGACY

European Space Agency

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cassini-huygens

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juice

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herschel

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planck

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exploration

exomars

Two missions comprising an orbiter to study the martian atmosphere, a landing demonstrator, a surface science platform and a rover to search for life below the surface.

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HERSCHEL
SCIENCE AND LEGACY

CONTENTS

→ FOREWORD

Some of the participants of "The scientific importance of submillimetre observations" workshop, held in Noordwijkerhout in May 1982, at the Keukenhof flower park.

Nervous people pretending to be calm at the Toucan viewing site in CSG, Kourou, only 5 km away from the Ariane 5 launcher shortly before the launch, from left to right: Matt Griffin (SPIRE PI), Albrecht Poglitsch (PACS PI), Sergio Volonte (ESA), Thijs de Graauw (HIFI PI), and Göran Pilbratt (ESA).

Equally nervous people at ESA's operations centre (ESOC) in Darmstadt, almost exactly one month after the launch and just about to send the manual command to open the Herschel cryocover.

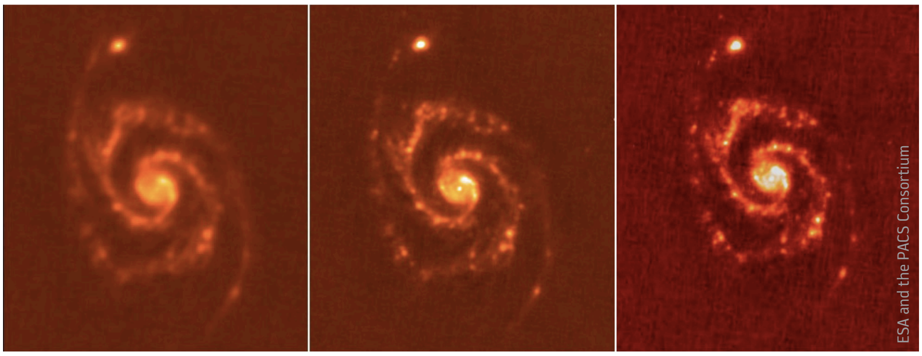
It is a pleasure and an honour for me to provide the foreword to this brochure that summarises the Herschel mission and its science achievements to date, capturing the basis for the science yet to come and its enduring legacy.

As alluded to elsewhere in this publication Herschel has a long history, and it is a privilege to have had the opportunity to participate in the Herschel voyage of discovery for almost 30 years, working together with so many talented and dedicated people. What started out as documents and reports, was made real, launched, operated (2009–2013), and eventually safely disposed of in a heliocentric orbit – predicted to return to the vicinity of its former working life in 2027.

Herschel was never dull, never routine, neither during implementation nor operations, not even during the 'routine' science phase. Over the years the mission was repeatedly challenged – technically, schedulewise, costwise, and also scientifically. The telescope primary mirror was to be made of carbon fibre, then aluminium, again carbon fibre, and finally silicon carbide. It was made of twelve segments, joined into a monolithic structure, but the first test joining two segments was not entirely successful. When the telescope was first tested under operational thermal conditions, the back focal distance was significantly different from the predicted one. Cooling was to be by cryostat, later by cryocoolers, and eventually we settled on using a superfluid liquid helium cryostat. In the cleanroom less than a year before launch there was a blockage in the cryostat, not once, but twice, and the first attempt at validating the crucially important alignment of the instruments inside the closed cryostat with the (fully passive) telescope sitting on top of it, failed miserably. The instruments had their own cliffhangers too. But all of these hurdles, and many more, were overcome and in the end Herschel was ready to be flown to Kourou for the launch campaign.

The launch, on 14 May 2009, was flawless and precisely a month later the cryocover was opened and for the first time Herschel could see the Universe. And so it did! The 'sneak preview' PACS M51 images confirmed excellent optical performance, the 'first light' SPIRE M66 and M74 images had 'noise' in the background that turned out to be distant galaxies, and HIFI performed terahertz heterodyne spectroscopy in space for the first time. Nobody involved will ever forget the HIFI malfunction that took place shortly afterwards. Nor will they forget when HIFI was successfully brought back into operation almost 6 months later.

Herschel's achievements are outstanding. Before Herschel, somewhere between a few hundred and a couple of thousand



Left: The Messier 51 galaxy (M51) as imaged by Herschel/PACS in the hours immediately following the opening of the cryocover. These 'sneak preview' images show M51 at 160, 100, and 70 μm wavelengths (from left to right), clearly demonstrating improving angular resolution with decreasing wavelength. This immediately demonstrated the quality and correct alignment of Herschel's optics.

Right: The memorable evening of the day after the cryocover opening in the basement of the Max Planck Institute for Extraterrestrial Physics in Garching with the team that made the very first Herschel 'sneak preview' observations into images. At the extreme right in the picture a very proud PACS PI Albrecht Poglitsch, more than 11 years after the PACS proposal was submitted.

'submillimetre galaxies' were known; in 16 hours of early science demonstration phase, mapping a 4x4 degree field, Herschel detected about 7000 such galaxies, and now hundreds of thousands have been catalogued. The highest redshift quasar known at the time was detected. The cosmic infrared background has been resolved into galaxies. Local ultraluminous infrared galaxies have been shown to harbour massive outflows of molecular material. The rate of star formation in galaxies appears to be controlled mainly by the availability of cold molecular gas. Herschel has imaged the entire Galactic Plane, as well as a number of low- and high-mass starforming molecular clouds. Filaments are seen at different scales; for nearby clouds it appears that most star formation takes place in filaments with densities above a critical value. In a spectral scan of the Orion Kleinmann-Low Nebula about 13 000 lines from 79 isotopologues of 39 molecules have been secured. Herschel has shown that the chemistry around evolved stars is more complex than previously thought, and that supernovae can produce prodigious amounts of dust. Water has been detected in a prestellar core, in young stars, in a protoplanetary disc, and has been extensively studied in our own Solar System. Herschel detected water on Ceres, showed that water from Saturn's moon Enceladus ends up in a torus around the planet, connected water in Jupiter's upper atmosphere with a cometary impact, and detected that water was 'Earth-like' in one comet, perhaps in two, but very significantly not in all. The list goes on...

Throughout its mission Herschel has observed targets near and far: the closest was a swiftly moving minor body observed after having passed within the orbit of the Moon, the farthest were galaxies (the current record is redshift z=6.95) whose emission has been travelling thirteen billion years before being detected – this is a range of more than 17 orders of magnitude in lookback time.

The enthusiasm emanating from the community has always been a much needed, and appreciated, source of energy for those of us in the front line. The atmosphere was electric among the participants in the 'Herschel Science Demonstration Phase Initial Results' meeting where Herschel observations were presented for the first time – in fact the meeting had to be moved outside ESA's establishment (ESAC) in Spain because there was no room large enough to hold all participants. Registration for the 'Herschel First Results Symposium', presenting the first science results submitted to the Astronomy & Astrophysics Special Issue, had to be curtailed due to fire regulations limiting the number of people who could be present at the symposium location in ESA's establishment (ESTEC) in the Netherlands.

The success of Herschel is the result of the collective effort of several hundred people in ESA, the instrument consortia, and industry that provided a unique space observatory enabling observations to be made that had never before been possible. The astronomy community embraced the opportunities

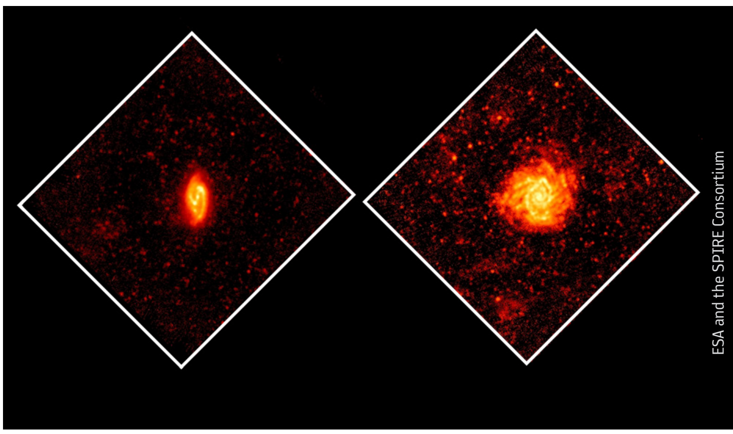
The first Herschel scientific results were presented in the 'Herschel First Results' symposium that took place on 4–7 May 2010. More than 400 astronomers came to ESTEC, Noordwijk to share in the excitement, presented 99 talks and 137 posters, and submitted over 100 papers.

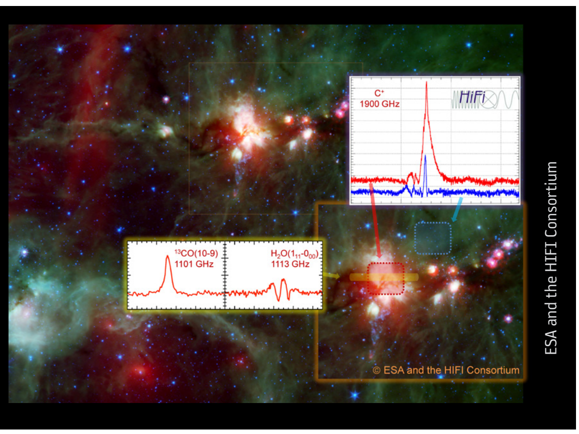
provided by Herschel, and thousands of researchers worldwide have been involved in the 2500 refereed scientific papers already published, with more appearing all the time. Herschel's legacy is literally growing by the day, and its data is and will remain an important asset for a long time to come.

My hope is that this brochure conveys some of the excitement that Herschel has generated so that it can be shared with as large an audience as possible, and that it serves as an inspiration for what needs to come in the future. Great missions do not die, and their data must not fade away!

Göran Pilbratt
Herschel Study & Project Scientist, 1991-2019

Left: Herschel/SPIRE first light images of the nearby galaxies M66 (left) and M74 (right). The 'noise' around the nearby galaxies is actually emission from far-away, high-redshift galaxies, thus SPIRE captured both the near and the far universe in its very first observations.
Right: Herschel/HIFI 'first light' THz spectroscopy of the DR21 massive starforming region. The background Spitzer/IRAC image displays the location of the water (H_2O), carbon monoxide (^{13}CO), and ionised atomic carbon (C^+) spectra. The spectra provide detailed diagnostics about the interstellar medium where young massive stars are creating massive outflows, wreaking havoc on their stellar nursery.





→ THE OTHER HALF OF THE LIGHT

As the first stars flickered into being, when the Universe was only about 200 million years old, they marked the end of the Universe's dark ages – the cosmic dawn had arrived. Since that time, roughly half of all the energy emitted in the Universe has been transformed into infrared radiation. Most of this infrared energy is carried by the far infrared, peaking at around 160 μm. This is because light has been absorbed by dust grains in the interstellar medium – the matter between the stars within galaxies – and the energy has then been re-radiated at far infrared wavelengths as dictated by the temperatures of these grains.

Without telescopes capable of seeing this long-wavelength radiation, astronomers would be missing half the energy in the Universe. Switching from visible light to infrared reveals marked contrasts. Dark dusty clouds in the optical become transparent in the near-infrared showing embedded and background stars, while in the far infrared wavelengths that Herschel was designed to study, the stars disappear and the clouds themselves shine brightly due to the long wavelength emission of the embedded dust.

This mosaic of images shows M31, the Andromeda galaxy, the nearest major galaxy to the Milky Way, as observed by Herschel in the far infrared (bottom right), and in the optical from the ground (top right). The Herschel image shows where raw material (cold interstellar matter) for star formation exists, and the optical image shows light from existing stars. On the left there is a composite image of both, displaying very clearly how the two relate to each other.

Thanks to Herschel, it is now clear that stars are far more than just beacons of light. They are engines of change that drive the appearance of their host galaxies. Sometimes their fierce radiation prompts more stars to form, at other times it stops the process in its tracks.

After almost 4 years of observing the cosmos, Herschel has revealed a remarkable story of star formation that it has traced from the nearest regions of the Galaxy to the most distant realms of space. This complex interplay between near and far has shown that we cannot uncover the full history of the Universe without studying the formation of stars in detail.

Before Herschel, we were literally in the dark about this drama because it takes place deep inside vast clouds of gas and dust that obscure our view at visible and near-infrared wavelengths. Herschel's predecessors in space were the US-Dutch-British Infrared Astronomical Satellite (IRAS); ESA's Infrared Space Observatory (ISO); NASA's Submillimeter Wave Astronomy Satellite (SWAS); the Swedish-led international Odin satellite; NASA's Spitzer Space Telescope; and the Japan Aerospace Exploration Agency's Akari satellite.

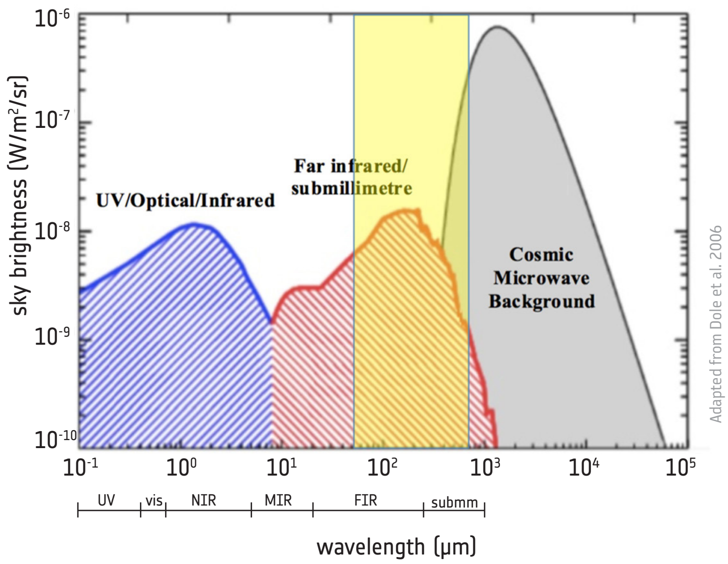
But Herschel was different. With its 3.5-metre aperture – it was the largest space telescope launched – and with instrument detectors sensitive to wavelengths that had either never previously been explored with such a large telescope, or even at all from space, Herschel has been able to show us these previously hidden realms in a way never achieved before.

Infrared light

The human eye is sensitive to the optical (or visible) part of the spectrum, covering approximately 0.4–0.7 micrometres (millionths of a metre, denoted μm). The infrared starts longward of the optical and extends to a wavelength of around 1 millimetre (1 mm = 1000 μm). Between 0.7 μm and 5 μm the radiation is known as the near-infrared (NIR), from 5 μm to 30 μm as the mid-infrared (MIR), while the far infrared (FIR) starts at wavelengths of around 30 μm. The longest wavelengths, beyond about 200–300 μm, are often referred to as the submillimetre. Although these subdivisions are not all firmly defined, there are important differences between these wavebands. For the shortest and longest bands there are 'spectral windows' where observations can be performed – with difficulty – by some ground-based facilities, but the 25–350 μm range can only be observed from space.

It is not only dust that shines in infrared; atoms and molecules of gas can also naturally give off infrared light. Unlike the dust, which emits over a large range of wavelengths to form continuum emission, the gas emits light only at specific wavelengths, which produce line spectra (see page 7). These contain much more information than the continuum emission. Analysing such spectra is like reading fingerprints; the identity of each type of emitter can be determined. Not only can the chemical composition of the object under study be revealed, but information about temperatures, motions, atomic abundances, chemistry, and other properties of the object under study can be obtained.

In revealing all of this and more, Herschel has provided a new, unique insight into the Universe. It has produced a huge database of observations that make up a legacy for astronomers to exploit for years to come. Most importantly, Herschel has explored the other half of the 'light' like no other mission before. In providing answers to many questions, Herschel has inevitably raised new ones that must wait for a future infrared space observatory to investigate.



The cosmic background from the ultraviolet/optical to the microwave part of the spectrum, the well known Cosmic Microwave Background (the CMB). In addition to the CMB there are two peaks, one in the optical/near infrared (the COB) peaking at around 1 μm, just longward of the optical, and another in the far infrared (the CIB) peaking around 160 μm. The COB and the CIB are made up of the integrated emission emitted since the end of the 'dark ages' in the early Universe. Herschel was designed to observe the Universe at wavelengths around (thus both shortward and longward of) the peak of the CIB.

→ TOOLS OF THE TRADE

Dust and gas together

The interstellar medium is the matter found between the stars in a galaxy. It is overwhelmingly composed of gas. Typically, 99 per cent of the mass in the interstellar medium is gas, atomic and molecular. The remaining one per cent is dust. Despite this, it can be easier to observe the dust. This is because more than 99 per cent of the gas is hydrogen and helium and neither of these emit much radiation at the frigid temperatures of the interstellar medium. For this reason, Herschel routinely observed the dust emission as a tracer of the gas, as well as taking advantage of some minor gas constituents, such as carbon monoxide (CO), ionized atomic carbon (C^+), and hydrogen fluoride (HF), to trace the gas and its properties too.

Continuum emission and line spectra

Radiation is emitted in two different forms: continuum and line spectra. Continuum radiation is emitted across a broad range of wavelengths. It is thermal in origin, arising from any 'solid' object, such as the dust grains found mixed in the gas of the interstellar medium, or a dense gas such as that found in a star.

A line spectrum is emitted by a tenuous gas. Atoms and molecules that make up the gas are in specific energy states. These states are determined by the structure of the atoms and molecules themselves, and the physical conditions of the gas. When they change into a lower energy state they emit photons to carry away the difference in energy. This corresponds to emitting corresponding specific wavelengths of radiation, producing what is known as line spectra.

The distribution of energy carried at each wavelength over a broad range is known as the spectral energy distribution (SED). Line spectra can be studied using spectrometers, which split incoming radiation into its constituent wavelengths. SEDs can be measured using low-resolution spectrometers, or in a coarser manner by observing at a number of different continuum bands.

Cosmological distances, redshift, and lookback time

The characteristic wavelengths associated with line emission from atoms and molecules can be used to help determine cosmological distances to distant objects in the Universe.

In a manner analogous to the Doppler effect, where sound waves shorten (rise in pitch) as a sound approaches and lengthen (lower in pitch) as the sound recedes, the wavelength of light from an object receding from us will be lengthened or 'redshifted'. Conversely, the light emitted from objects that move towards us will be 'blueshifted'.

To express the distance to far distant objects astronomers use the cosmological redshift, represented by z. Unlike the Doppler shift, which depends on the motion of the object when the light was emitted, the cosmological redshift is due to the expansion of the Universe itself. An observed redshifted line will have the wavelength $\lambda_{obs} = \lambda_{em} (1 + z)$, where λ_{em} is the emitted wavelength which can be measured in the laboratory.

The scale factor $(1 + z)$ is the factor by which the wavelength has increased, the same factor by which the size of the Universe has increased while the photon has been travelling from when it was emitted to when it was detected. Given the redshift z (which is directly observed) and a number of parameters that define the Universe, importantly the Hubble constant (H_0) and the total (baryonic plus dark) matter fraction (Ω_m), the time the photon has travelled can be calculated. This time is called the lookback time because we see the object as it was this much back in time.

Examples for illustration, with a Hubble constant H_0 = 67.5 and total matter fraction Ω_m = 0.31, for a flat Universe whose current age is 13.8 billion years.

As can be seen except for very small redshifts this scale is not linear; already at z=1 the lookback time is more than half the age of the Universe, for redshifts of a few we are in the early Universe, and for redshifts of 6 and larger we are within the first billion year of cosmic history. All photons with redshifts larger than 0.42 were emitted before the Earth had even formed, 4.6 billion years ago, when the Universe was at 67 per cent of its current age.

Redshift (z)	Lookback time (billion years)	Universe age (billion years)	% of Universe's current age
0.1	1.35	12.5	91%
0.5	5.21	8.62	62%
1	7.96	5.87	43%
2	10.5	3.29	24%
4	12.3	1.54	11%
6.95	13.1	0.77	5.6%

→ THE HERSCHEL MISSION

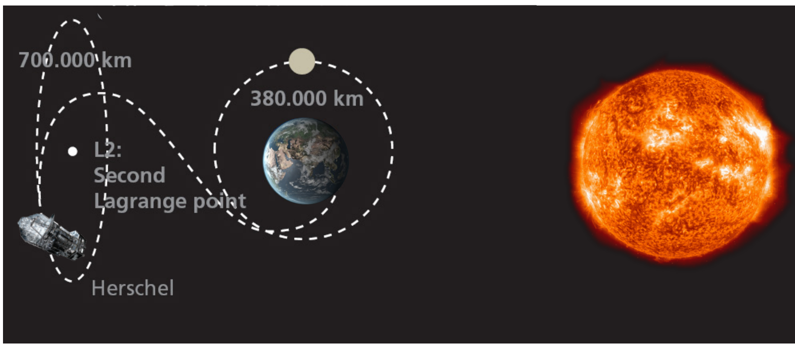
Launch of Herschel and Planck on flight V188 by an Ariane 5 ECA from CSG, Kourou in French Guiana at 10:12 local time (13:12 UT) on 14 May 2009.

Herschel was launched into space on 14 May 2009. Carried aloft by an Ariane 5 ECA from French Guiana, it was released from the launcher within half an hour of liftoff, having been injected towards its operational 'large halo' orbit around the gravitational L2 point, situated 1.5 million kilometres from the Earth in the anti-sunward direction. During the operational phase of its mission, Herschel's distance from the Earth varied between 1.2 and 1.8 million kilometres.

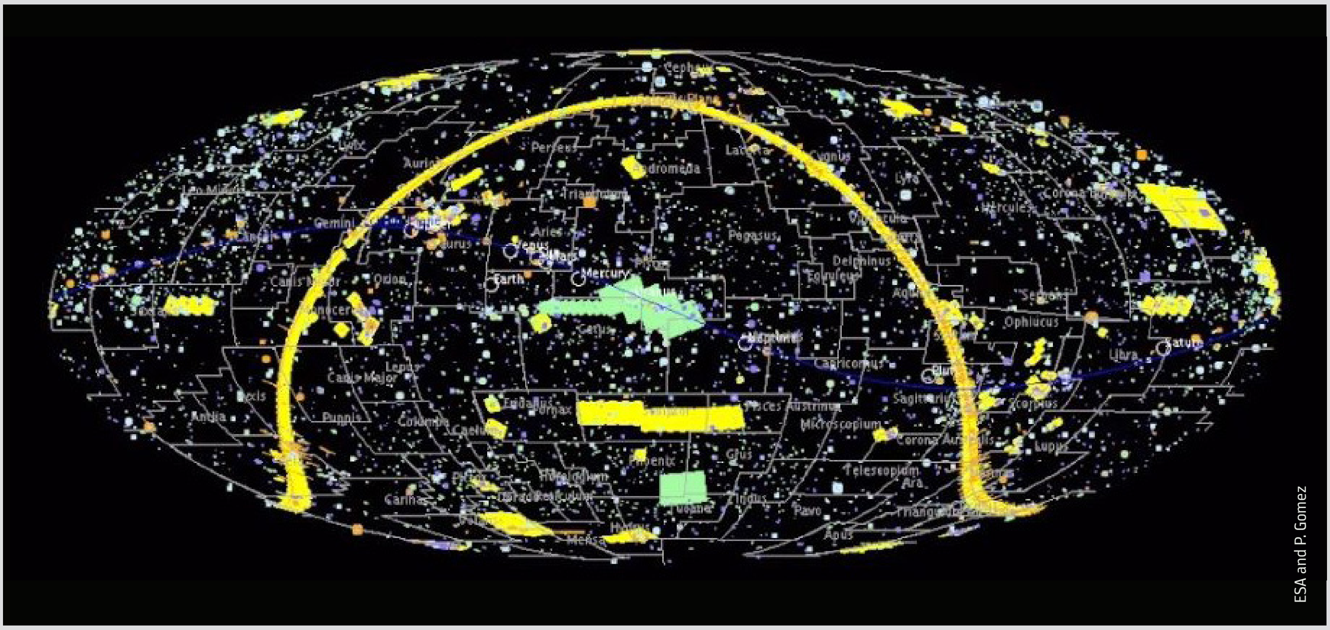
Equipped with 2300 litres of superfluid liquid helium – required to provide the necessary working environment for the science instruments that were mounted on an optical bench inside the cryostat – Herschel set to work. The 'sneak preview' and 'first light' images and spectra from its instruments were obtained in June 2009 and the first science observations followed soon after. Until it ran out of helium on 29 April 2013, Herschel was an indefatigable workhorse. The telescope collected 23 400 hours worth of science data from over 37 000 observations representing 698 different observing programmes. A further 2600 hours were spent on 6600 routine science calibration observations.

The data produced by all the Herschel observations are available in the Herschel Science Archive held on servers at ESA's European Space Astronomy Centre, near Madrid in Spain. It is a publicly accessible database and provides an enduring legacy from the mission.

To date Herschel data have been used in more than 2500 scientific papers. Since 2012 every year 250 or more papers based on Herschel data have been published every year in the refereed scientific literature.



The orbit of Herschel around L2, the second Lagrange point of the Sun-Earth system, situated 1% farther away from the Sun than the Earth. Figure not to scale.



A plot of all Herschel's observations on the celestial sphere. The picture has been made from the real schedule files; yellow designates PACS/SPIRE 'parallel mode' and green SPIRE large area surveys, easily identified in the picture (e.g. the yellow horseshoe-shaped Galactic plane survey, see pages 12-13), blue PACS photometry, and white HIFI, PACS, and SPIRE spectroscopy combined (fields are too small to be easily seen in the picture).

The history of Herschel

The interest for a space observatory operating in the far infrared and submillimetre spectral range emerged in the late 1970s. At the time, near-infrared observations with ground-based telescopes were revealing obscured embedded sources not seen in the optical, and radio astronomers had just begun to explore the new field of astrochemistry. There was clearly more waiting to be discovered in this relatively uncharted region of the electromagnetic spectrum, and this could only be done by going into space.

Herschel began life as the Far InfraRed and Submillimetre space Telescope (FIRST), which was proposed to ESA in November 1982 in response to a call for mission proposals issued in July of that year. FIRST then underwent a feasibility study, conducted in 1982–83. Soon afterwards ESA's Horizon 2000 programme was conceived and FIRST was one of 77 mission concepts submitted for consideration. In 1984 it was chosen as one of the programme's four cornerstone missions, the others being the missions today known as SOHO and Cluster (which together form one cornerstone), XMM-Newton, and Rosetta.

Throughout the 1990s a variety of mission, telescope, spacecraft, and payload configurations were studied. In 1993 FIRST was selected as Cornerstone 4. The three instruments were selected in early 1998, based on an Announcement of Opportunity issued the autumn before, and were confirmed in 1999.

During the symposium "The promise of the Herschel Space Observatory", held in Toledo in December 2000, FIRST was renamed the Herschel Space Observatory, to mark the 200th anniversary of the discovery of infrared light by William Herschel. Industrial implementation commenced in April 2001, and in February 2009 the largest infrared space telescope ever built and the first space observatory to scrutinise the sky at longer, submillimetre wavelengths, was flown by a huge Antonov cargo plane to Kourou to prepare for launch.

Finally, on 14 May 2009, Herschel took to the skies, en route to its operational orbit around L2. During almost four years of operations, which ended only when the liquid helium supply was exhausted on 29 April 2013, Herschel studied some of the coldest – and some not quite as cold – objects in space, from nearby in our Solar System to the farthest reaches of the Universe.

→ GATHERING THE LIGHT

Herschel's 3.5-metre aperture telescope collected the infrared light and fed the three complementary instruments that made up the science payload. The challenge of making a space telescope is that on the one hand it must be as light as possible, and on the other hand strong enough to survive launch and able to deliver its designed optical performance under the conditions to be encountered in space. Thanks to the use of a new material, silicon carbide (SiC), and a new manufacturing process, Herschel's 3.5-metre diameter telescope only weighed 315 kilograms. It delivered excellent optical performance and also – important for an infrared telescope – very low emissivity, minimising the still very considerable telescope background emission. The telescope had no moving parts, and this demanded extensive testing, before launch, under operational conditions, as well as precise on-ground alignment with the instruments, which were mounted on an optical bench inside the closed cold cryostat. An additional complication was the need to align the unseen instruments, via reference markers on the exterior of the cryostat, with the telescope, which was at ambient temperature, taking into account that final operational conditions in space would be just below 90 K (-183°C).

The instruments were selected from responses by scientists to an Announcement of Opportunity that was issued by ESA in October 1997.

PACS (**P**hotodetector **A**rray **C**amera and **S**pectrometer) was a camera and a low- to medium-resolution imaging spectrometer that worked between the wavelengths of 55–210 µm, in the far infrared region.
SPIRE (**S**pectral and **P**hotometric **I**maging **RE**ceiver) was a camera and a low- to medium-resolution imaging spectrometer that worked between the wavelengths of 194–671 µm, often referred to as the submillimetre region.
HIFI (**H**eterodyne **I**nstrument for the **F**ar **I**nfrared) was a single-pixel very high resolution spectrometer. It worked between the wavelengths of 157–210 µm and 236–615 µm.

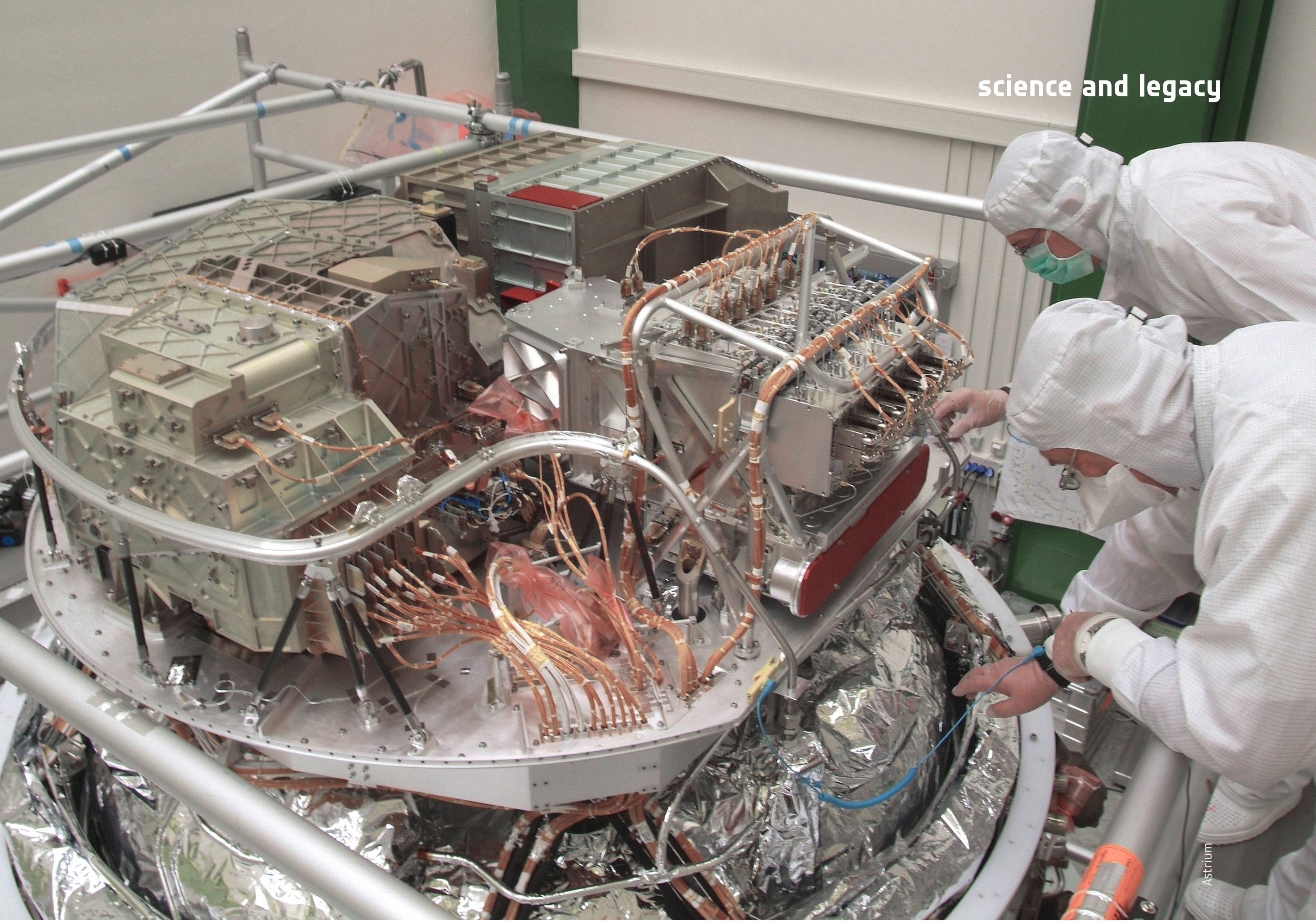
Herschel's instruments exploited three different detection techniques in order to provide astronomers with the most comprehensive far-infrared information it was possible to obtain.

As the name of the Heterodyne Instrument for the Far Infrared suggests, this particular high-resolution spectrometer used the heterodyne principle. By 'mixing' the astronomical signal with a reference ('local oscillator') signal the former was translated into a much lower frequency, which could then be more easily amplified and filtered and the information extracted. The frequency of the reference signal could be tuned within a wide range of frequencies that in turn meant the instrument could work over a wider range of far-infrared wavelengths than ever before.

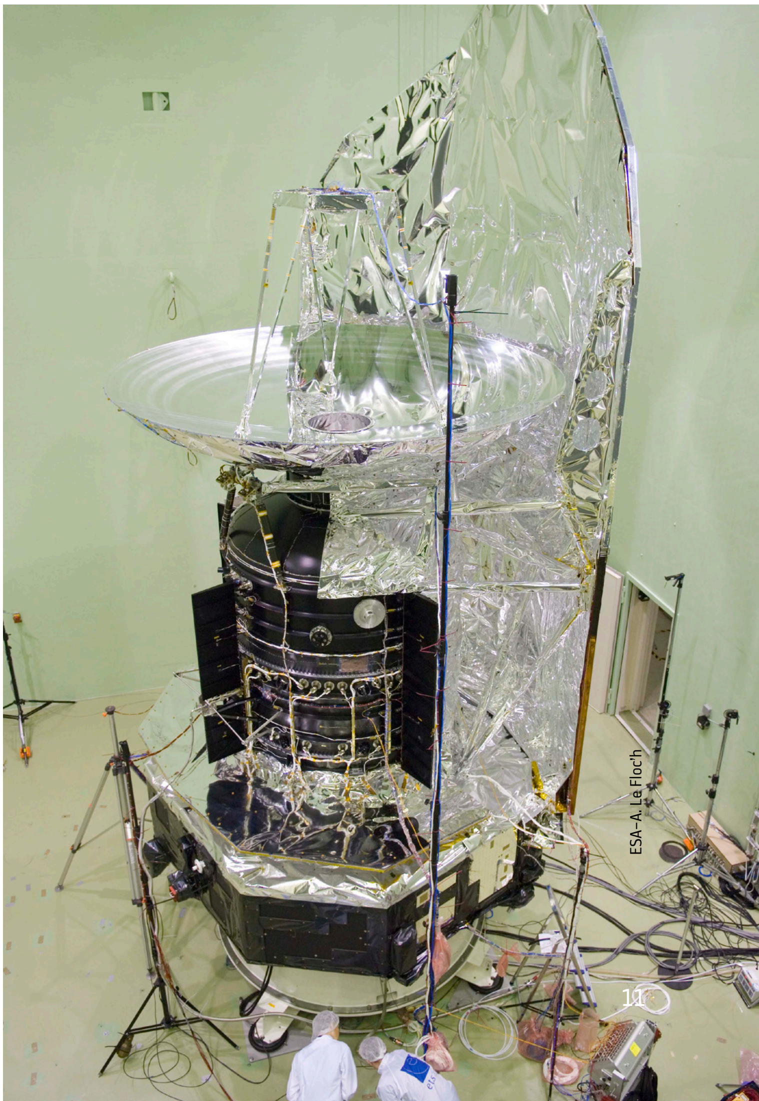
The Photodetector Array Camera and Spectrometer (PACS) and the Spectral and Photometric Imaging REceiver (SPIRE) could both work in one of two modes, either as multiband imaging photometers, or as imaging spectrometers, using a variety of detector technologies.

In spectrometry mode, PACS used photoconductors, while SPIRE used bolometers. Photoconductor materials exhibit electrical resistances that depend on how much infrared light is falling upon them. Connected into electrical circuits they can be used to determine the amount of infrared radiation coming from celestial objects. Bolometers are sensitive to the incident radiation through a change in temperature when the power is absorbed, which can be accurately measured.

Test preparations underway on the Herschel telescope in the ESTEC cleanroom in 2008.



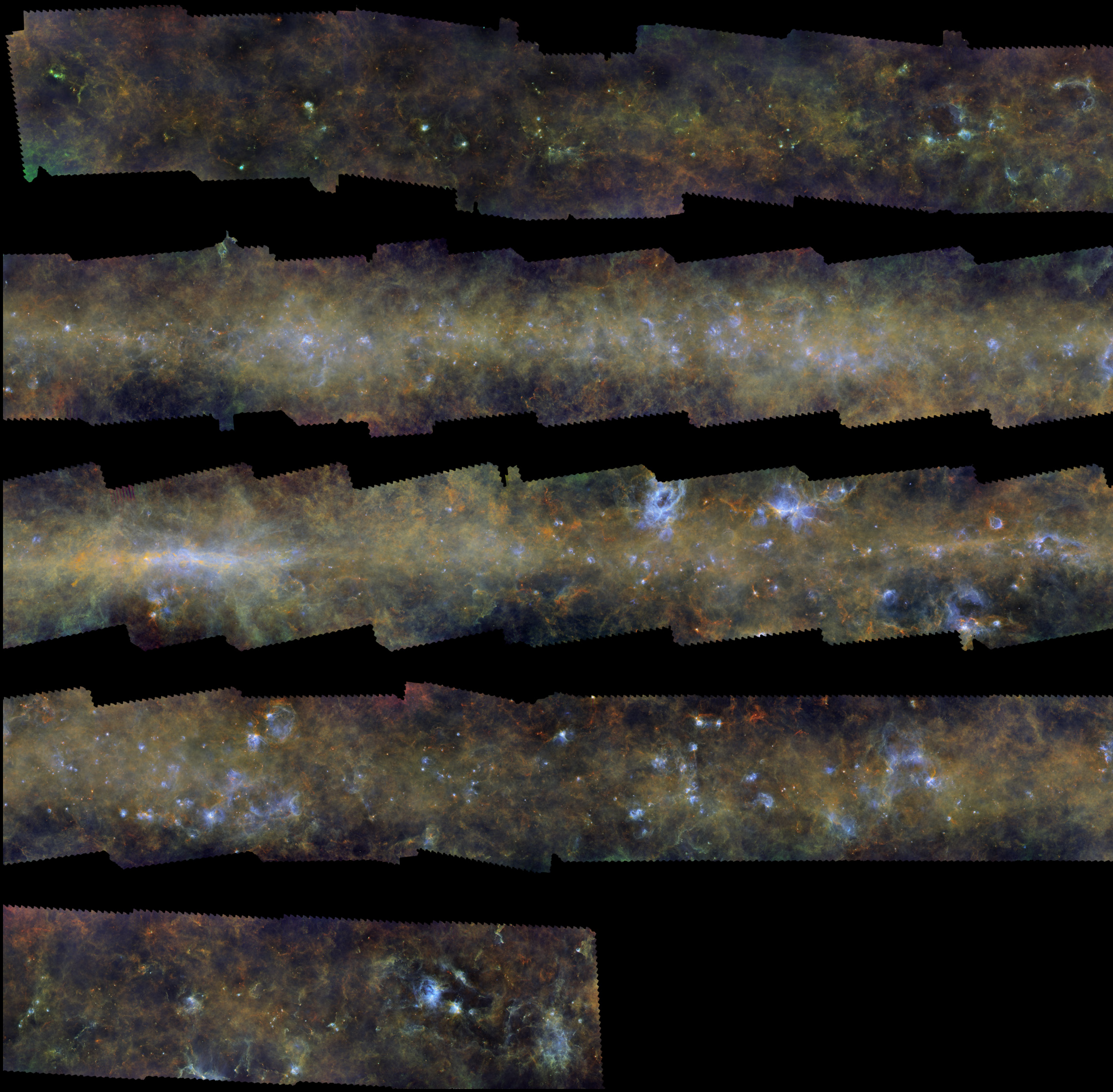
Top: The integration of the three instruments' focal plane units (HIFI (front-right), PACS (front-left) and SPIRE (back)) in July 2007 at the Astrium facility in Friedrichshafen.
Bottom: The Herschel spacecraft undergoes final preparations inside the Large European Acoustic Facility (LEAF) at ESTEC in Noordwijk for the acoustic tests on 5 and 6 June 2008.



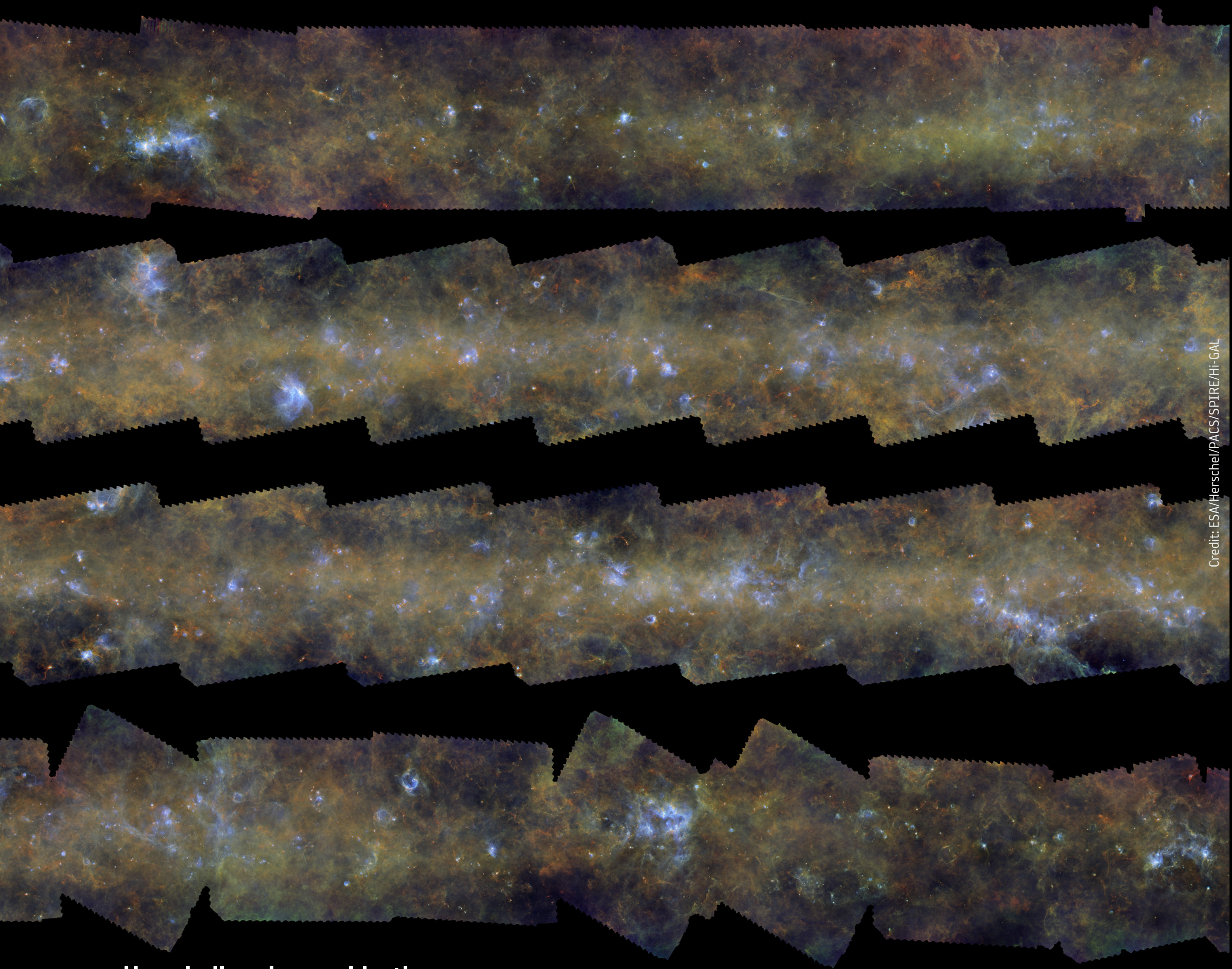
PACS and SPIRE could also be used as cameras to take images in two (PACS) or three (SPIRE) bands simultaneously. In this mode of operation, they both used bolometers, albeit of very different kinds, having in common the very low operational temperature of only 0.3 K (-273°C) furnished by dedicated coolers. The PACS photoconductors and HIFI mixers had operational temperatures of approximately 2 K (-271°C), obtained directly through the cryostat inside which they were mounted on an optical bench.

There is a pleasing historical resonance in the use of bolometers on the Herschel Space Observatory. When William Herschel discovered the infrared region of the spectrum, he did so using thermometers to investigate the heating ability of light in the various colours of the rainbow. He noticed that the thermometer he placed just beyond the red light experienced the greatest heating of them all. Thus, he concluded, there were invisible rays that carried great heat. In effect, he was using the thermometers as bolometers. The bolometers used onboard Herschel were approximately a million times more sensitive than William Herschel's thermometers.

→ THE INFRARED UNIVERSE



Herschel has surveyed the full 360 degrees of the Galactic Plane in five colours (70 and 160 µm by PACS, 250, 350, and 500 µm by SPIRE) by conducting approximately 1000 hours of 'parallel mode' observations with PACS and SPIRE operating together. Here just under 40% of the Galactic Plane is displayed (from Galactic longitude +68 to -70 degrees), the Galactic Centre is visible in the second 'tile' (square) from the left in the the third row from above.



Herschel's science objectives

Herschel was conceived to provide close to 20 000 hours of science observing time, the majority of which was offered to the general astronomical community through a standard competitive proposal process. The major science areas foreseen were:

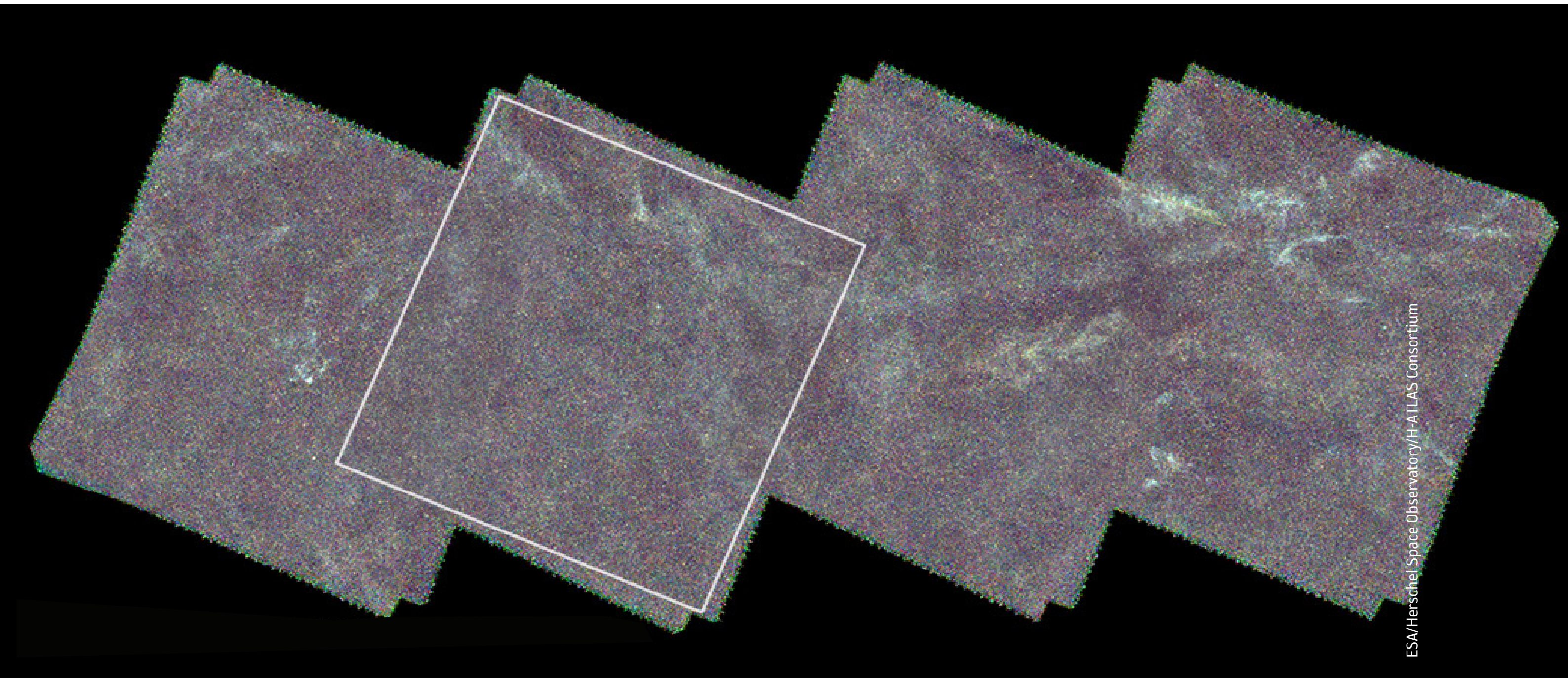
- Wide-area surveys of the galactic and extragalactic sky to measure dust-enshrouded star formation activity throughout cosmic time;

- Detailed studies of the physics and chemistry of the interstellar medium, in our own Galaxy as well as in external galaxies;

- Observational astrochemistry of gas and dust as a tool for understanding the stellar and interstellar lifecycles and for investigating the physical and chemical processes involved in star formation and stellar evolution, including gas and dust disks around young, main sequence, and evolved stars;

- Investigation of Solar System objects and their atmospheres, including minor bodies such as planetary satellites, asteroids, comets, and trans-Neptunian (Kuiper belt) objects.

→ ORIGINS



Herschel-ATLAS coverage of four 'tiles', each measuring 4x4 degrees (more than 60 times larger than the full Moon), on the Galactic equator in five bands (100, 160, 250, 350, and 500 μm). The white square indicates the Science Demonstration Phase (SDP) field, consisting of about 16 hours of observing time, during which approximately 7000 galaxies were identified. The entire H-ATLAS survey has catalogued hundreds of thousands of galaxies.

For most of history, the Milky Way was known only as a band of wispy light across the dark night sky. That all changed in 1610 when Galileo lifted his telescope to his eye and looked upwards – the Milky Way then resolved into countless numbers of individual stars.

In the latter years of the 18th century, William Herschel and his sister Caroline began to count those stars. William called the technique "star gauging" and his aim was to determine the distribution of the Milky Way's stars throughout space.

However, it was not until the 1920s that we came to realise that the Milky Way is our home galaxy, containing hundreds of billions of stars. With this knowledge we have never been able to look at the night sky in quite the same way again. Now, Herschel has done something similar for the very distant Universe.

In the 1990s, astronomers discovered that a faint fog of infrared light bathes the Universe. They called it the cosmic infrared background (CIB) radiation. In October 2009 and November 2010, Herschel targeted two specific regions of the sky, one in the north and one in the south. Known as the Great Observatory Origins Deep Survey (GOODS), these regions are windows into the deep Universe. In a little over 360 hours of observations, Herschel resolved the infrared background radiation in the north field into 300 galaxies, and the south field into 800.

These galaxies are all extremely distant, their light having taken between a few billion to more than 10 billion years to cross the gulf of space between them and the observatory. Herschel data provided the brightness of these galaxies at far infrared wavelengths – with this information the star formation rate of the individual galaxies at the time can be estimated.

Herschel was conceived with the investigation of the cosmic history of star formation in mind. A key question for it to answer was: how do most stars form? In the present day Universe, most galaxies form stars at a leisurely pace, producing just a handful of stars every year. The exceptions to this rule are galaxies that are colliding with each other. In these mergers, intense episodes of star formation, known as starbursts, can be triggered as giant clouds of interstellar gas are forced together.

Astronomers suspected that galactic mergers might have been responsible for the higher pace of star formation at its peak, about ten billion years ago, but hints from the Spitzer Space Telescope and, later, more robust evidence from

J. Silk, 1997 ('The Far InfraRed and Submillimetre Universe' ESA Symposium at Grenoble, France):
"Galaxy formation cannot be understood without incorporating a detailed theory of star formation."

Herschel surprisingly revealed that this was not in general the case.

In spite of their higher production rates, most galaxies at earlier cosmic epochs seem to be quite 'ordinary'. Their greater productivity is likely to arise simply because cold molecular gas – the raw material to make stars – was more plentiful at those times.

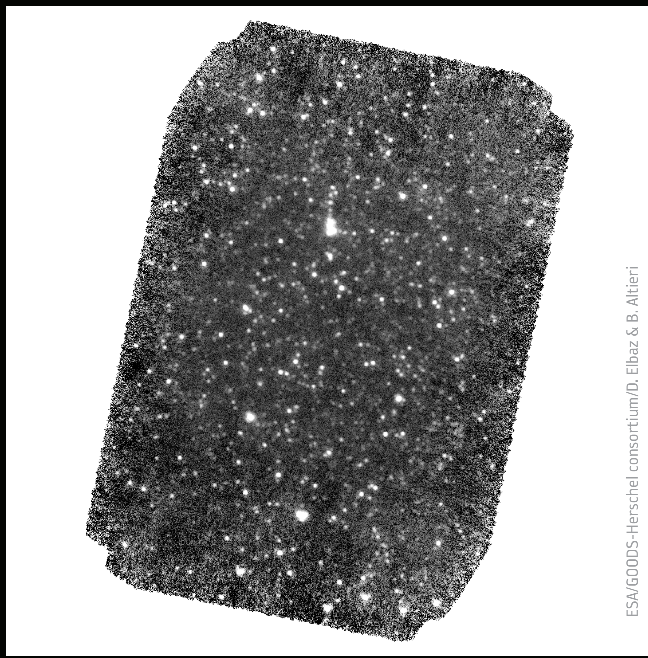
Within this scenario, earlier galaxies are not concealing any mysterious mechanism that boosts their star-making efficiency, but are most likely just scaled-up versions of the galaxies we observe at the present time.

This result relegates merger-triggered starbursts to a minor role in the total history of star formation. However, they are the most prodigious star forming galaxies at any particular epoch. In fact, the decisive ingredient seems to be the availability of cold molecular gas, which could well be provided by intergalactic streams – as suggested by computer-based simulations of cosmic structure formation.

In addition, Herschel established that, at any given time in the most recent 10 billion years in the Universe, the vast majority of starforming galaxies seem to obey a very simple rule: the more stars a galaxy already has, the faster it is forming new stars. This relation is now called the Galaxy Main Sequence.

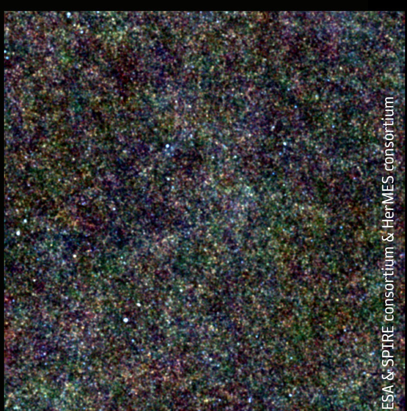
That such a relation seems to be true across most of cosmic history is remarkable, suggesting that relatively simple mechanisms must be regulating the complex process of a galaxy turning its interstellar material into stars.

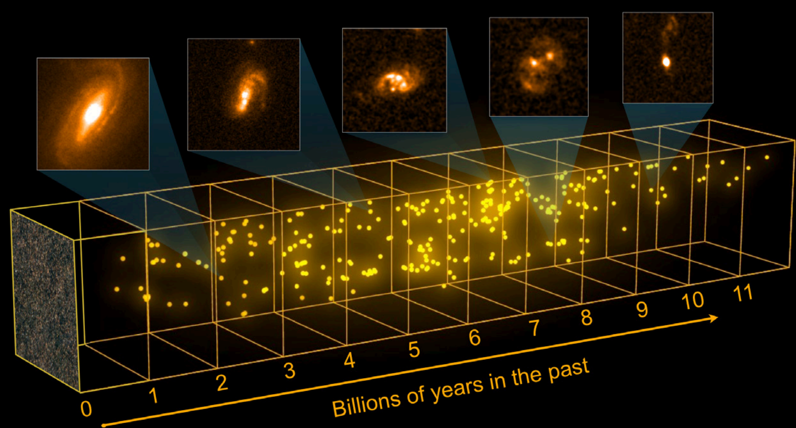
Herschel also showed that galaxies can be forming stars at rates of hundreds or even thousands of times higher than our Galaxy today. In general, in the most recent 10 billion years, the younger the galaxy with a certain mass of stars, the more stars it will form.



A 10x15 arcmin (about 15x20 million light years) part of the GOODS-South field, as seen by the PACS instrument at 100 μm. The central ~ 8x8 arcmin in this field amassed 206 hours of observations and shows sources with fluxes of less than 1 mJy, the lowest in any Herschel extragalactic field.

Interestingly, Herschel has found a population of massively starforming galaxies in the very early Universe. A prime example is HFLS3, a distant galaxy that was unknown until Herschel. It shows up as a faint, red smudge but is forming stars at least a thousand times faster than the Milky Way. With a redshift of z= 6.34 it is seen when the Universe was less than 900 million years old and represents a whole class of galaxies shown by Herschel to have star formation rates that exceed that of our own Milky Way by thousands of times. That such massive – and massively star forming – galaxies existed when the Universe was so young was not entirely expected and strains our theories of how structure formed in the very early Universe.

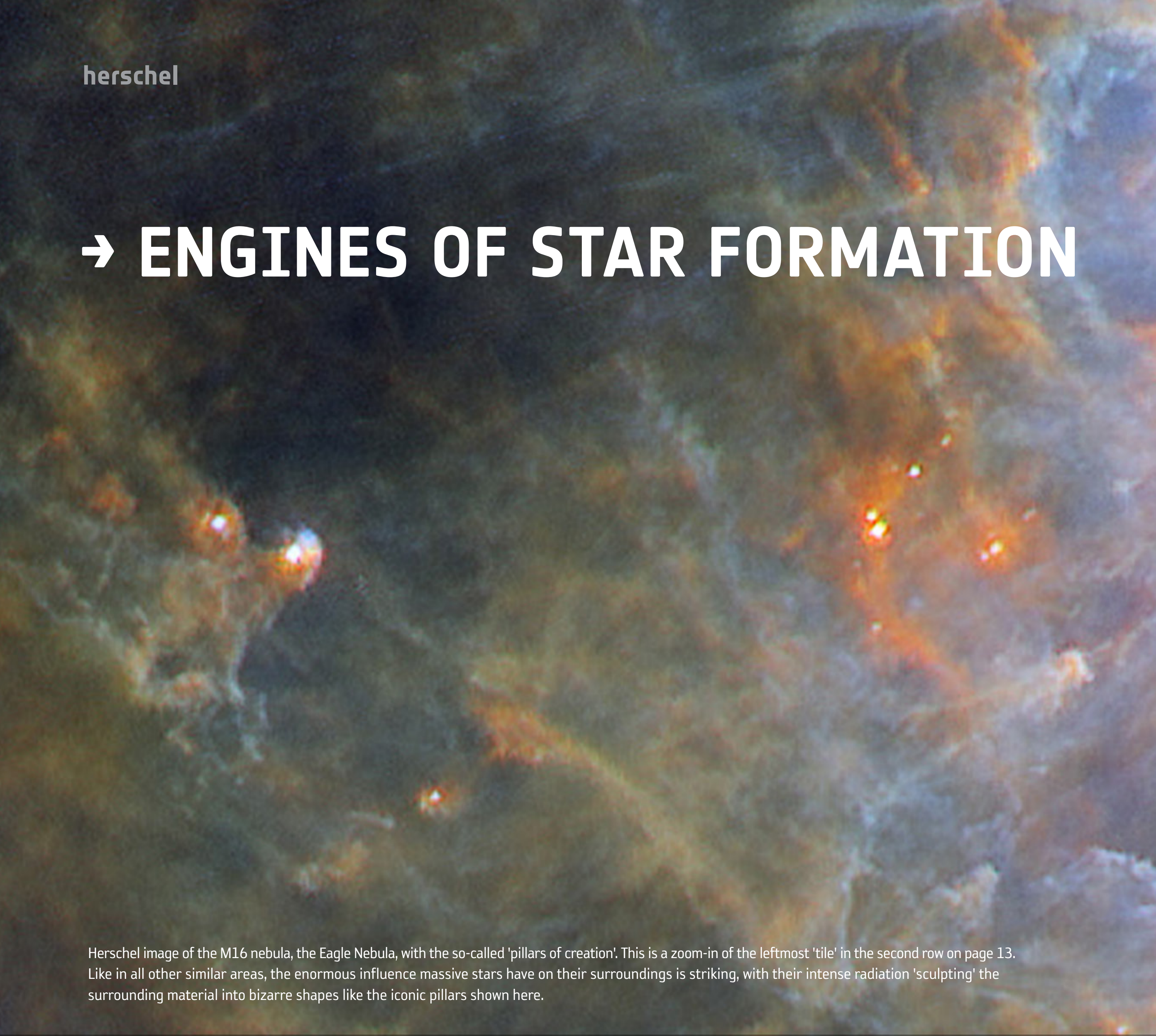




ESA - C. Carreau/C. Casey (University of Hawai'i); COSMOS field: ESA/Herschel/SPIRE/HerMES Key Programme; Hubble images: NASA, ESA

Left: A Herschel/SPIRE image of the Lockman Hole, a patch of the sky located in Ursa Major (the Great Bear). This 'clean' area has little foreground emission and is therefore popular for galaxy surveys. Every 'grain' in the picture is a distant galaxy.
Right: By measuring redshifts of individual galaxies a three dimensional picture can be constructed, where the third dimension is lookback time (see page 7), and thus galaxy evolution and star formation can be studied across the history of the Universe.

→ ENGINES OF STAR FORMATION



Herschel image of the M16 nebula, the Eagle Nebula, with the so-called 'pillars of creation'. This is a zoom-in of the leftmost 'tile' in the second row on page 13. Like in all other similar areas, the enormous influence massive stars have on their surroundings is striking, with their intense radiation 'sculpting' the surrounding material into bizarre shapes like the iconic pillars shown here.

Spiral galaxies, such as the Milky Way, are threaded with gas and dust that make up the interstellar medium. The gas accounts for about 99 per cent by mass, the remaining one per cent is dust. The conversion of this material into stars and its eventual return to the interstellar medium after the star dies is the engine that drives the formation and evolution of a galaxy.

Giant molecular clouds are huge complexes of interstellar matter. Their density is mostly very low, much thinner than the air we breathe, indeed much thinner even than the best 'vacuums' we can create in our laboratories. Yet many of these clouds are the sites of vigorous stellar birth. The question is: how does the extremely diffuse mixture condense into compact cores, which later evolve into stars?

Herschel provided a unique opportunity to study the very early, enshrouded stages of star formation in unprecedented detail. The mission spent 460 hours targeting nearby starforming regions. Collectively these regions are called the Gould Belt as they make up an incomplete ring (when viewed on the sky) of starforming complexes, about 3000 light years across.

As part of this survey, the telescope revealed an intricate network of filamentary structures. Although some filaments had been seen before, Herschel showed them to be ubiquitous. They were present in all the molecular clouds that the spacecraft observed, however, not all of them make stars. An obvious question to ask is: why not? What determines whether a given molecular cloud will make stars or not?

Analysis of the Herschel data suggests that turbulence in the giant molecular clouds creates the tangle of filaments in the first place. Then, in the filaments that are massive enough, gravity takes over, pulling the gas together to form the dense cores within which stars form.

Credit: ESA/Herschel/PACS/SPIRE/Hi-GAL

Once stars begin to form, they accumulate, or accrete, mass from their surroundings. This is thought to happen through a disc of material, a bit like water spiralling into a plughole. It is during this phase that the initial masses of the stars are set.

Having used Herschel to study embryonic stars in the Orion Nebula, astronomers were surprised to find that some of these young stellar objects were varying their brightness by more than 20 per cent over just a few weeks. Instead of a smooth flow of matter from the surroundings through the accretion disc and onto the star, clumps of gas are thought to bear down on the disc, heating it when they strike and resulting in a temporary brightening. Another explanation is that these gas clumps could orbit the star, casting shadows that dim the star.

Whatever the case, star formation is anything but a smooth, uniform process.

A key investigation for Herschel has been into a process called feedback. This is the way star formation affects a galaxy's ability to make more stars. When a star is born, it begins to emit radiation as both energy and particles. Both can push gas around. Sometimes the compression triggers further star formation, and at other times it leads to an increase in the turbulence in a region, which hinders further stellar births.

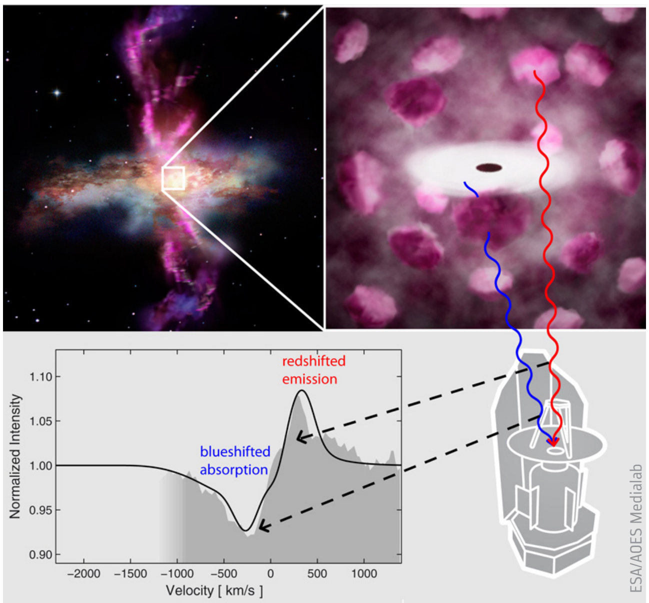
One of Herschel's most important results is to show that such feedback is not just limited to the immediate environments of star formation but can affect whole galaxies.

Ultra-Luminous InfraRed Galaxies (ULIRGS) that shine with 1000 billion times the luminosity of our Sun were discovered by IRAS and studied by ISO. They are relatively 'local' galaxies produced by the merger of gas-rich galaxies and, as their name suggests, they are much brighter in the infrared than at visible wavelengths.

In a study of ULIRGS, all of which were star-bursting mergers, Herschel detected raging winds of molecular gas streaming away from almost every single one of them. These ubiquitous galaxy-wide winds are thought to be driven by the intense emission of light and particles from young stars, or by shockwaves generated by the explosion of massive stars associated with the starburst event, or by central supermassive black holes. In at least one case, the activity has been proven energetically feasible to be triggered by the blast of radiation given off as matter swirls around feeding a supermassive black hole at the centre of the galaxy.

However they are formed, these winds are immensely powerful. The fastest of them are blowing at more than 1000 kilometres per second, or about 10 000 times faster than the wind in a terrestrial hurricane. Such winds are capable of removing 1200 times the mass of the Sun from their host galaxies every year. Unchecked, they could remove the raw material to generate any more stars on timescales of just a few to tens of millions of years or so, very short times in a galaxy's lifespan.

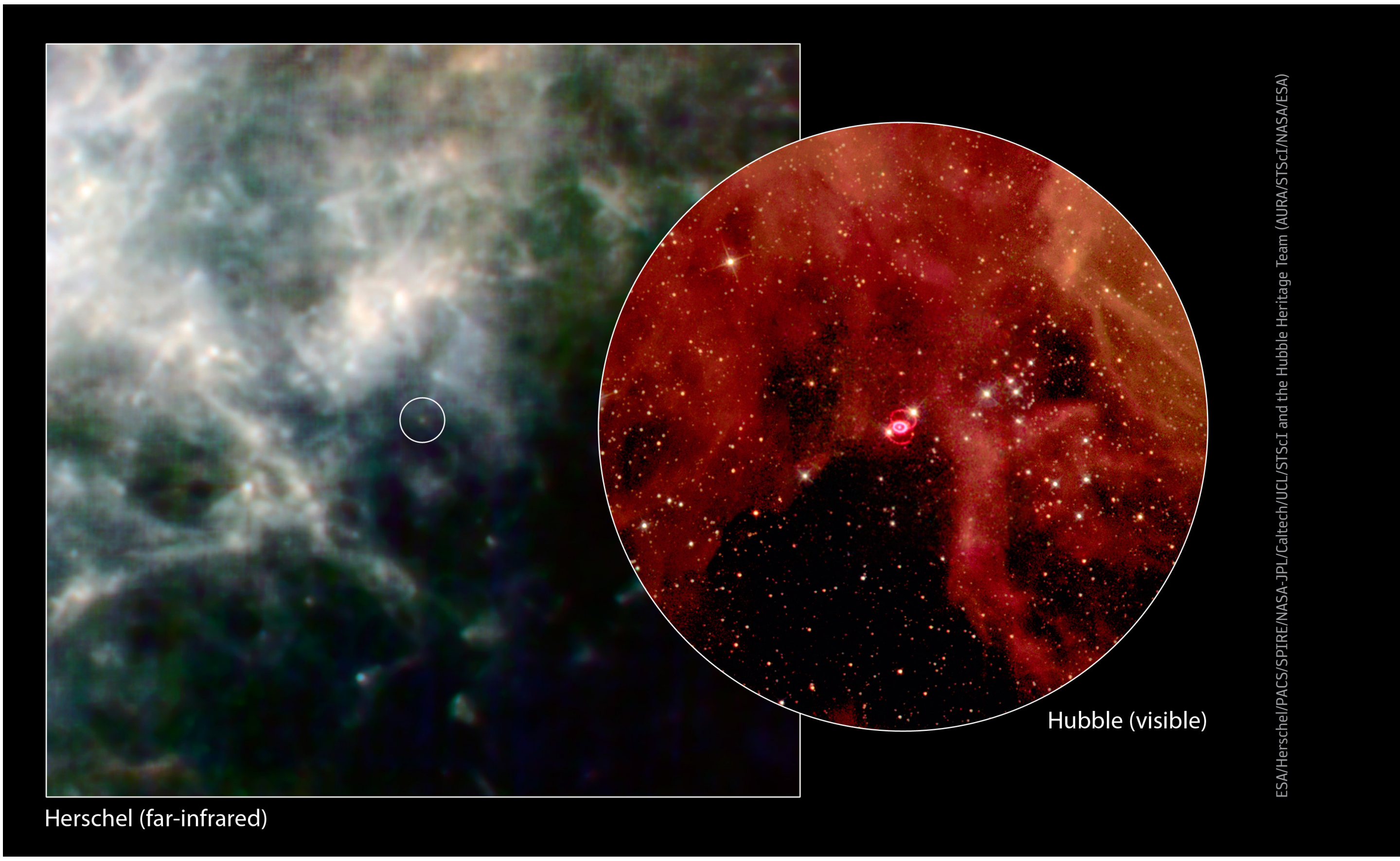
ESA and SPIRE & PACS consortia, Ph. André (CEA Saclay) for Gould's Belt Key Programme Consortia



Top: Illustration showing how outflows of molecular gas can be detected in the spectra of galaxies. The outflows are traced via molecular spectral lines, here of the hydroxyl molecule (OH) 79 μm line in Mrk 231, that exhibit a distinctive blue- and red-shifted profile due to the geometry of the system as viewed from Herschel.
Left: Six hundred newly forming stars are crowded into intricate filaments of gas and dust that make up this stellar nursery in the Aquila constellation, seen for the first time by Herschel.
Bottom: This image shows Rho Ophiuchi, a vast stellar nursery where new stars take shape from billowing clouds of gas, in a Herschel colour-composite view.

ESA/Herschel/NASA/JPL-Caltech, CC BY-SA 3.0 IGO; Acknowledgement: R. Hurt (JPL-Caltech)

→ FROM DUST TO PLANETS



This mosaic shows the region surrounding the remnant of the famous supernova SN1987A as observed by Herschel (on the left) and the Hubble Space Telescope (on the right).

Planetary systems are the by-products of star formation. They condense out of the matter in the protoplanetary accretion disc surrounding a newly formed star. Herschel has allowed astronomers to study these discs at far-infrared wavelengths in unprecedented detail.

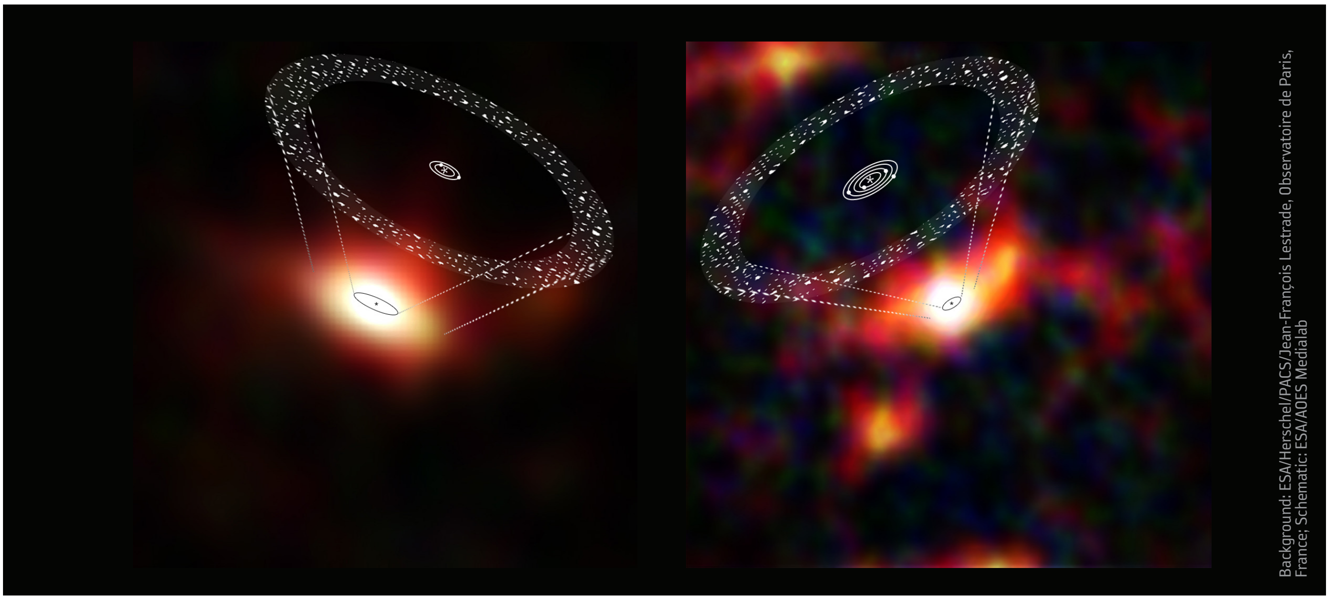
Thanks to Herschel we know that these planet-forming discs can be extremely massive. Around TW Hydrae, a 10-million-year-old star, Herschel has shown that there is surprisingly still enough mass to build 50 Jupiter-sized planets. This is unusual because if the star is really this age, then astronomers would have expected the dusty disc to have dissipated. Either it will be 'blown away' by the wind of particles from the star or the forming planets will have absorbed some of it and expelled the rest.

Herschel is allowing us to study diverse planetary systems in a unique way. Gliese 581 and 61 Virginis are two nearby stars that astronomers already know to have planets orbiting them. Unlike our own Solar System, however, these stars do not possess large planets like Jupiter and Saturn.

Herschel's contribution has been to reveal that the two stars are also surrounded by large quantities of cold dust. This is thought to have come from a multitude of collisions between comets. It implies that comets must be much more plentiful around those two stars than they currently are in our own Solar System. This may be because they have no large planets.

In our own Solar System, the gravitational fields of Jupiter and Saturn are thought to have triggered a comet shower in which a multitude of these icy bodies bombarded the planets in their

J. Silk (Cosmic Vision event at UNESCO, Paris, France, 2004):
"We will never fully understand planet formation if we do not understand star formation in the first place."



The debris disc around the star 61 Virginis (left) and around the star Gliese 581 (right) as seen with Herschel at far-infrared wavelengths.

final stages of formation. But without such large planets to trigger the deluge, most of the comets remain in orbit around Gliese 581 and 61 Virginis.

Around the bright, young star Fomalhaut, the situation is even more extreme. Herschel has revealed a massive dust belt with temperatures between 40K (-233°C) and 100 K (-173°C). To sustain the belt, which would normally be blown away by the pressure of the star's light, there must be a constant series of collisions. Every day, the equivalent of either two 10 kilometre-sized comets or 2000 one-kilometre-sized comets must be completely crushed into small fluffy dust particles to account for the infrared signal seen by Herschel.

It implies that some trillions of comets must orbit the star in this relatively narrow belt. In our own Solar System, a similar number are thought to exist but scattered widely by the gravity of the giant planets into the Oort cloud.

Herschel may also have put astronomers on the track of where the dust came from in the first place. The telescope's unrivalled ability to detect the emission from cold dust in both the near and distant Universe has shown that there is a lot of dust out there, even at extremely early times. The puzzle is that the stars take billions of years to turn into the red giant stars that are known to produce dust. Herschel may have found the answer in exploding stars.

Known as supernovae, these ill-fated stars live fast and die young. Each detonation is the final act of a massive star's short life. In 1987, a stellar explosion was observed in the Large Magellanic Cloud, a satellite galaxy of the Milky Way. Dubbed supernova 1987A, the expanding shockwave has been travelling through space ever since.

In 2011, Herschel mapped the Large Magellanic Cloud and, unexpectedly, astronomers found that the remnant of the supernova could be identified. In the wake of the shock wave, there was enough dust to form more than 100 000 Earths. This is a staggering amount and if typical for supernovae would be more than enough to provide the dust that Herschel observes in the early Universe. The trouble is that as the debris continues to expand, other shock waves develop that travel back towards the site of the supernova. This reverse shock passes back through the dust and could very well destroy it. So, although supernova 1987A is an intriguing result, it is not clear whether the dust survives in significant quantities to explain the earlier, dusty Universe. Follow-up observations are needed of other, older supernova remnants.

→ THE WATER TRAIL

We all instinctively understand one of the crucial roles that water plays on Earth. Without it, there could be no life on our planet. However, the origin of the water on Earth is veiled in mystery, so finding water elsewhere in the Universe is a crucial step in determining how it found its way to our planet in the first place.

In 2012, Herschel found a vast stock of water in a cloud of dust and gas called Lynds 1544. Known as a prestellar object, Lynds 1544 is on the verge of collapsing into a new Sun-like star. As the star forms, astronomers expect that planets will also take shape around it. Herschel's measurements show that there is enough water vapour in Lynds 1544 to fill Earth's oceans 2000 times over.

In such clouds, the water is usually found frozen in a layer around individual dust grains. It is turned into vapour, molecule by molecule, by far-ultraviolet radiation, allowing them to evaporate. In its frozen solid form, water does not emit infrared radiation visible to Herschel. Calculations have shown that for there to be 2000 Earth oceans worth of water vapour, there must be three million Earth oceans worth still frozen onto the dust grains in Lynds 1544.

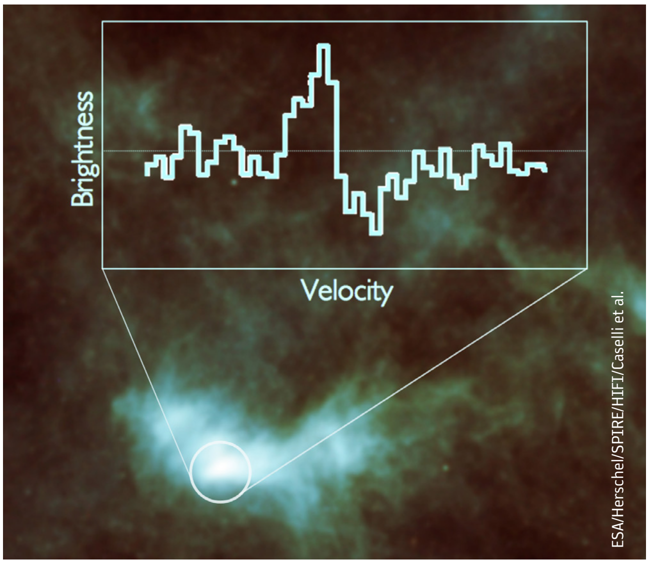
A similar signal was found in the disc around the young star TW Hydrae. The disc is made of dust and gas that is expected to eventually form planets. This was the first star for which water vapour was detected inside a planet-forming disc, and suggests that there is a large stock of water that could be incorporated into the subsequent planets.

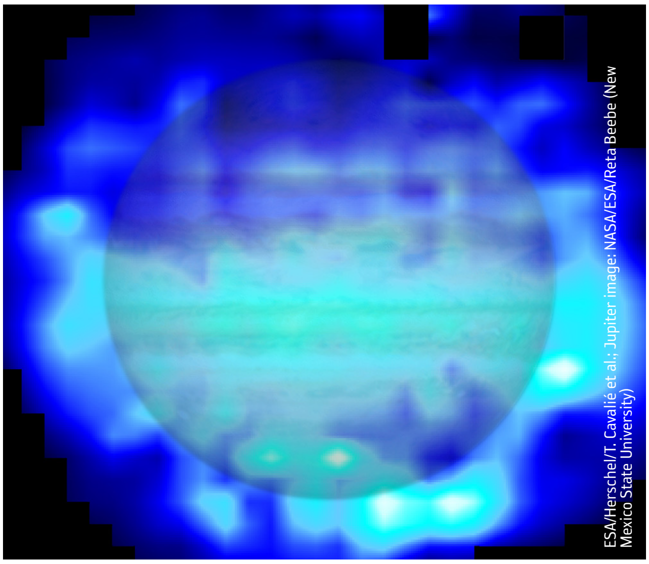
In the case of our own planet, Earth's oceans are thought to have been at least partially filled by the collision of water-rich bodies long after its formation and the collision that produced the Moon. This is because our planet formed at such high temperatures that its original stock of water is expected to have evaporated. Yet today, two-thirds of the surface is covered in water; this must have been delivered from space after Earth cooled down, but what is the source?

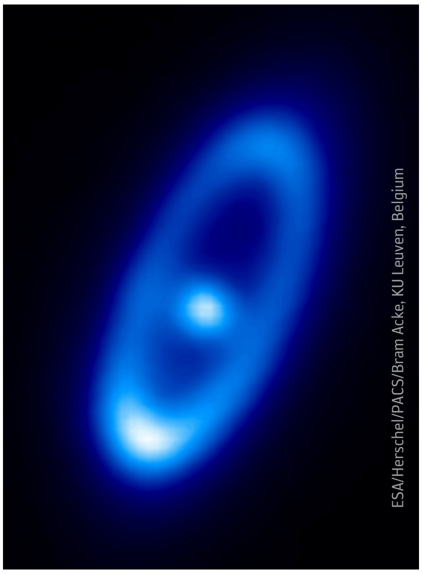
Although water is always made of hydrogen and oxygen, the isotopes of those elements can be different. Studying Comet Hartley 2, Herschel showed that its water has almost the same isotopic composition as Earth's oceans. This was the first time a comet was observed to have Earth-like water.

Herschel contributed two more observations to the debate, finding that Comet Honda-Mrkos-Pajdušáková probably also contained Earth-like water. But another comet, known as 2009 P1 (Garradd), had a different isotopic blend from that of our planet's water. More recently, the ESA Rosetta mission has shown that the water evaporating from Comet 67P/Churyumov–Gerasimenko has an isotope composition very different from that of Earth's.

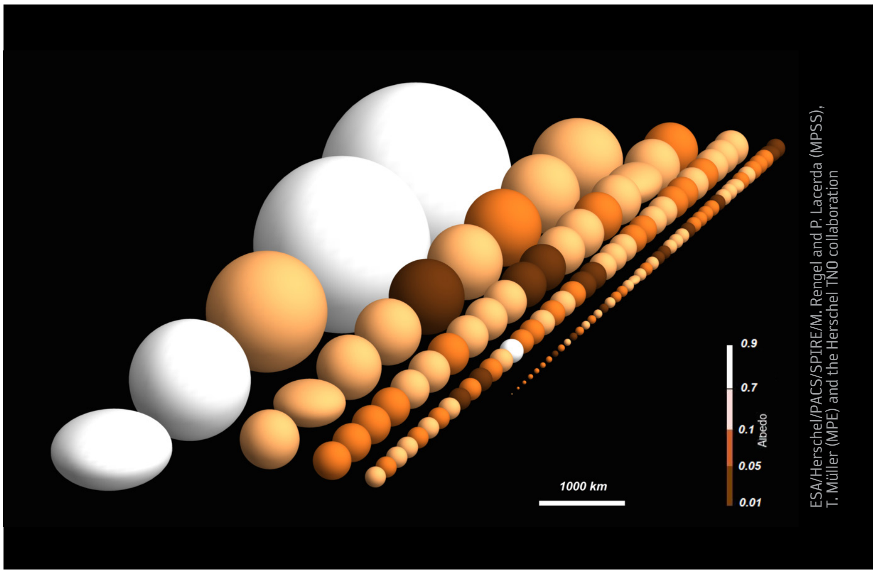
Left: The discovery of water (in the form of vapour) in a prestellar object in the Taurus molecular cloud. The Herschel/HIFI water spectrum is displayed on top of a Herschel/SPIRE image showing the location of L1544.
Right: This map shows the distribution of water in the stratosphere of Jupiter as measured by Herschel. White and cyan indicate highest concentration of water, and blue indicates lesser amounts.







This image shows the thermal emission from the young star Fomalhaut.



Herschel has observed 132 of the known 1400 TNOs, cold worlds that inhabit a region of the Solar System beyond the orbit of Neptune, some 4.5–7.5 billion km from the Sun.

Putting all the information together, it is currently thought that a broad and diverse range of minor bodies contributed to the critical role of bringing water to our planet – this may include a fraction of the water coming from comets with the 'right' isotope blend.

Elsewhere in the Solar System, Herschel has shown that the uppermost layers of Jupiter's atmosphere still contain water vapour from the 1994 impact of Comet Shoemaker-Levy 9. The temperature of the planet's atmosphere means that the water cannot have risen from within because there is a 'cold trap' above the visible clouds that separates them from the stratosphere above. Water vapour would condense in this trap if it tried to rise from below.

At Saturn, it is not comets but one of the moons that is raining water on the planet. Enceladus is expelling around 250 kilograms of water vapour every second. Herschel observations show that much of this finds its way to Saturn, where it eventually condenses, although the clouds it forms are too faint to be seen.

Herschel has proved itself to be a powerful tool in searching for and studying water in a range of circumstances. Its unique sensitivity and spectral range has allowed astronomers to not just look for the molecule but to begin investigating the mechanisms that bring water from areas of star formation in molecular clouds, through protoplanetary disks, to the surfaces of planetary bodies.

The remnants of planet formation

Out beyond the orbit of Neptune, some 4.5–7.5 billion kilometres from the Sun or about 30 – 50 times farther from the Sun than Earth, lies a region of smaller worlds. These 'trans-Neptunian objects', or TNOs, include Pluto and the other more recently discovered dwarf planets Eris, Haumea, and Makemake, as well as a host of smaller bodies.

There are 1400 known TNOs but this is probably just the tip of the celestial iceberg. They almost certainly make up a huge population of objects in the distant reaches of the Solar System and are important because they are thought to be some of the most primitive remnants of the planet-forming era. Their properties are therefore essential for testing different models of the Solar System's formation and evolution.

Being so far from the Sun, TNOs are particularly cold, with temperatures of around 40 K (-233°C). This makes them excellent targets for Herschel, which observed ten per cent of them during its lifetime. The Herschel measurements of their infrared emission, together with the amount of light reflected from their surface – measured by optical observations – provide their sizes and the fraction of light reflected, a quantity known as the albedo.

Their properties are striking because of their diversity. Sizes range from just below 50 kilometres to almost 2400 kilometres in diameter; Pluto and Eris are the largest. The differing albedos imply a variety of surface compositions. Low albedos are an indication of dark surface materials, such as organic compounds, while higher albedos are suggestive of pure ices. However, intriguingly and unexpectedly, such high albedo icy surfaces must be geologically young, suggesting at least some of these 'remnants' must be geologically active.

→ AN INTERNATIONAL ENTERPRISE

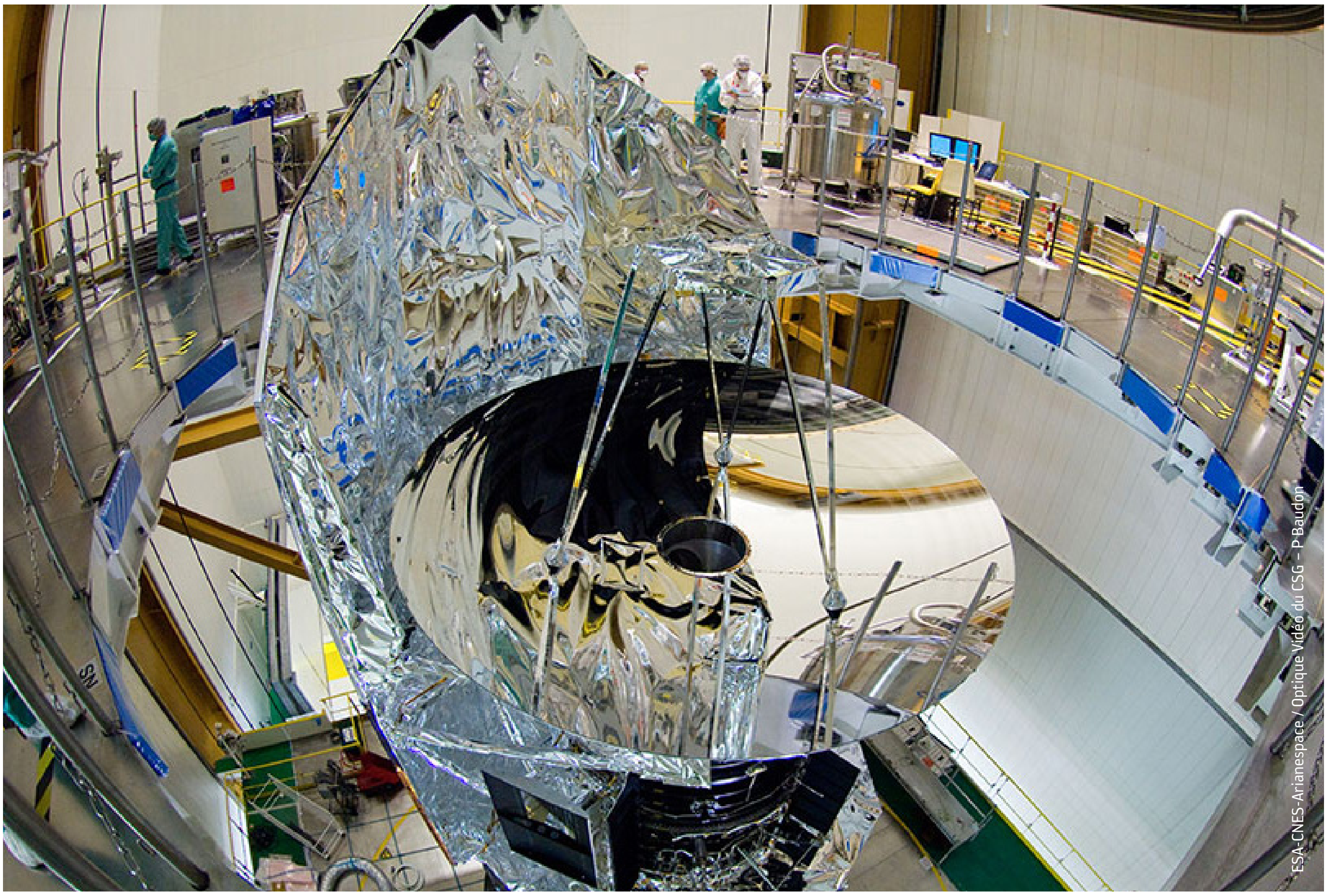
Sixteen ESA Member States[1], as well as a number of international partners[2], have contributed to the making of Herschel, including its instruments. The prime contractor responsible for bringing the industrial consortium together was Thales Alenia Space (Cannes, France). Astrium (Friedrichshafen, Germany) supplied the payload module, where the instruments and telescope sat. The Thales Alenia Space industry branch (Turin, Italy) provided the service module where essential satellite systems such as power and communications and warm instrument electronics were located. Astrium (Toulouse, France) provided the giant telescope itself. More than 100 industrial partners contributed, and the instrument consortia typically comprised one to two dozen participating institutes each.

Herschel mission operations were conducted by the Mission Operations Centre (MOC) at ESA's European Space Operations Centre (ESOC) in Darmstadt, Germany. The Herschel Science Centre (HSC), the location for the science operations team, was located at ESA's European Space Astronomy Centre (ESAC) in Villanueva de la Cañada in Spain – this is now home to the Herschel Science Archive. An additional centre was the NASA Herschel Science Center (NHSC) located at the California Institute of Technology Infrared Processing and Analysis Center, Pasadena, California, USA.

Although the Herschel instrument control centres (ICCs) were spread across Europe, there was one interface to the Herschel Science Centre for each instrument: for PACS it was the Max Planck Institute for Extraterrestrial Physics, Garching, Germany; for SPIRE it was the Rutherford Appleton Laboratory, Didcot, UK; and for HIFI it was SRON Netherlands Institute for Space Research, Groningen, the Netherlands.

[1]Austria, Belgium, Denmark, Finland, France, Germany, Ireland, Italy, the Netherlands, Norway, Poland, Portugal, Spain, Sweden, Switzerland, and the United Kingdom
[2]Canada, China, Israel, Russia, Taiwan, and the United States of America

The integration of Herschel in the rocket fairing as viewed from inside the final assembly building in Kourou.



→ A LASTING LEGACY

The Herschel mission leaves behind a lasting legacy in the form of a treasure trove of data, thousands of scientific papers, and a new generation of astronomers whose professional lives have been formed by working on this remarkable endeavour.

Herschel has made important discoveries and vital contributions to almost every field of astronomy and planetary science. Its main discoveries illuminate star formation, both in our Milky Way galaxy and in galaxies throughout the history of the Universe. They also trace key molecules – among them, water – from interstellar clouds to growing planetary systems, and the mission has investigated the chemistry of interstellar clouds and touched on the properties of black holes.

Yet there are still many unanswered questions and, as always in science, a wealth of unanticipated questions that have emerged from the new discoveries. These open questions are also part of Herschel's legacy. They will shape the future study of the Universe for years and decades to come.

Herschel's data were eagerly awaited, and indeed many astronomers have started their scientific career with Herschel. In addition to the many papers well over a hundred PhD theses present research related to Herschel – and likely many more are hidden in university libraries across the world.

This new generation of astronomers is now applying the skills and expertise learnt with Herschel to planning and developing the next generation of astronomical observatories.

Indeed, the infrared Universe remains a place in which there is still much to explore and Herschel has helped set the agenda for its future investigation.

Whereas the visible part of the spectrum comprises wavelengths that vary by a factor of two from blue to red light, the shortest infrared wavelengths are a factor of 1000 smaller than the longest. This is why astronomers split infrared into near-infrared, mid-infrared, far-infrared, and (sometimes) submillimetre regimes.

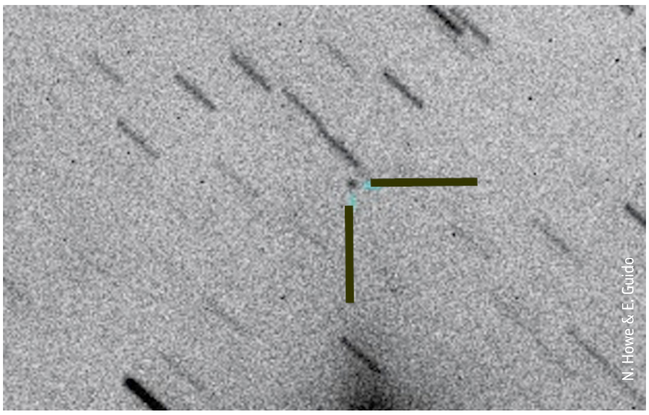
Although it means that the treasures to be found in the whole infrared spectrum are widespread, it also means that comparing one infrared telescope to another is not an easy thing to do. Each individual space telescope is optimised to cover specific wavelengths that allow it to reach its scientific goals.

Herschel's concentration on the far infrared and submillimetre regimes was designed to allow it to study relatively cool objects across the Universe, with a particular focus on unlocking the formation and evolution of stars and galaxies, and the relationship between the two.

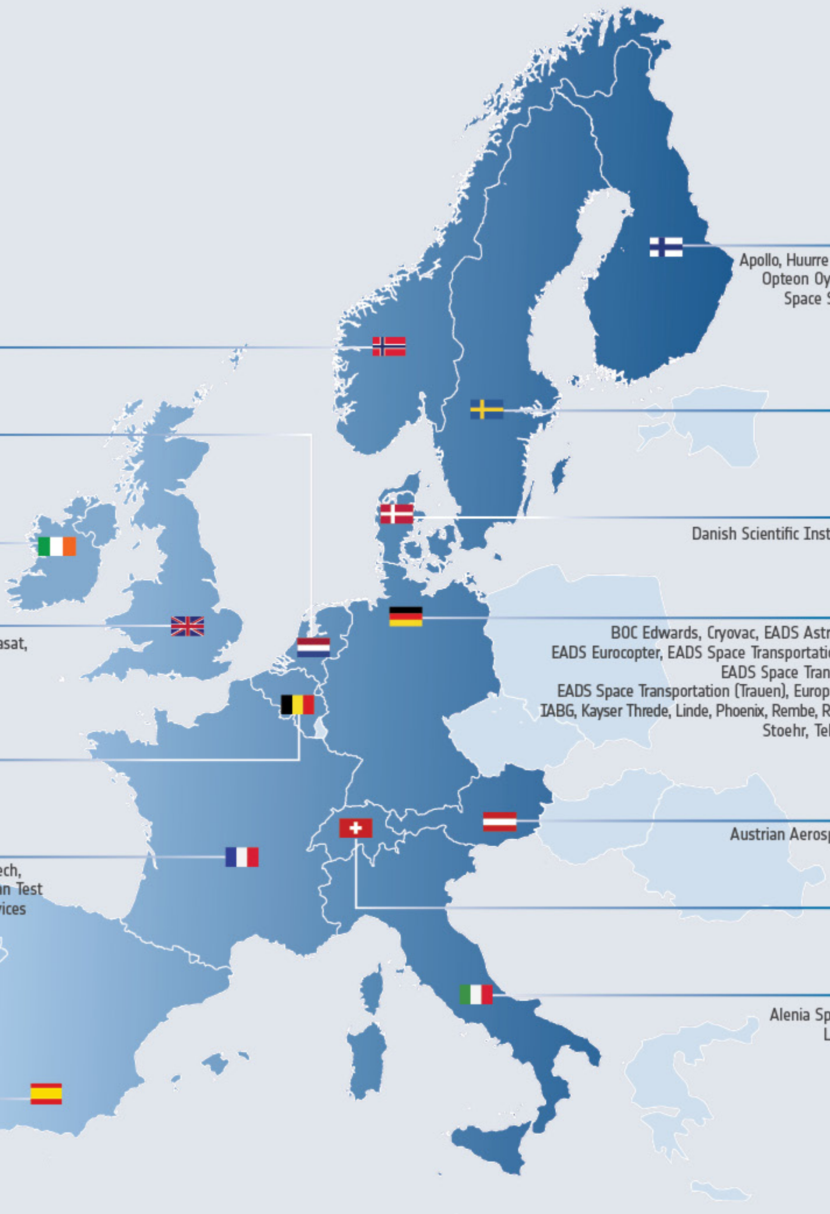
The James Webb Space Telescope (JWST) is a joint venture between NASA, ESA and the Canadian Space Agency. With a primary mirror of 6.5 metres diameter it is optimised to observe from 0.6 µm to 28 µm. These are shorter wavelengths than Herschel and have been chosen to continue the investigations pioneered by the Hubble Space Telescope. By observing these wavelengths, JWST can look into the more distant Universe where ultraviolet and optical light are stretched by the expansion of the Universe into the infrared. In particular, JWST will study the first stars and galaxies. It will also be used to investigate in more detail how nearby stars and planets form.

It is not just space-based observatories that will follow-up the work started by Herschel. Located in Chile, the Atacama Large Millimetre Array (ALMA), built by the European Southern Observatory and international partners, is a giant array of fifty 12-metre antennas. The shortest wavelengths that can be seen by ALMA overlap with the longest that could be seen by Herschel. Many former Herschel users are increasingly requesting time on ALMA to further their studies of interesting celestial objects. In particular, observing debris discs around other stars and the giant molecular winds discovered by Herschel to be streaming from the nearby ultraluminous infrared galaxies quickly became favourite targets for ALMA.

Herschel bridged the gap in the electromagnetic spectrum between the observations of previous infrared space missions and those performed with ground-based facilities. Although there are ongoing studies, there is no space observatory confirmed for the coming decade to keep exploring these wavelengths. This only adds to the importance of Herschel's data and scientific heritage.



Herschel as a dot moving away from its operational orbit into its 'disposal' orbit around the Sun, captured by the Faulkes North telescope on 27 June 2013. The telescope is tracking the motion on the sky of Herschel, thus the stars become lines.



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