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The *Herschel* Space Observatory: results and expectations one year after launch

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Abstract

Launched on 14 May 2009, the *Herschel* space observatory is now fully operational since more than one year ago, and is providing us already with a totally new view of our Universe at far infrared and submillimeter wavelengths. With its 3.5 m diameter primary mirror, *Herschel* is the largest space observatory ever launched into space and it carries onboard three science instruments, whose focal plane units are cryogenically cooled inside a superfluid helium cryostat. Here we present a few highlights of the main scientific results obtained by this mission in its first year of in-flight operations. The results obtained by *Herschel* cover all astrophysical areas, from our Solar System to the most distant galaxies. As originally envisaged, *Herschel* is allowing us to study with an unprecedented detail the mechanisms which govern the formation of stars in our Galaxy and beyond, as well as to determine the star formation processes that took place in other galaxies when the Universe was only one tenth of the age it has now. In addition, *Herschel* is providing us with a wealth of spectral information about the chemical constituents of the interestellar and circumstellar medium, delivering data which may be crucial to understand many aspects related to the overall chemical evolution of our Universe and, in particular, the origin of water in our Solar System and of the complex molecules which are known to be the building blocks of life. With a designed lifetime of at least 3 full years of routine scientific operations *Herschel* has a promising future ahead and many more exciting results are yet expected to come in the next few years.

1 Introduction

ESA's *Herschel* space observatory [10] was successfully launched, together with the Planck satellite, on board an Ariane 5 ECA launcher from Kourou, the European's Spaceport in French Guiana, on 14 May 2009. Equipped with a passively cooled 3.5 m primary mirror, *Herschel* is the largest telescope ever launched into space, orbiting around the second Lagrangian point of the Sun-Earth system (L2), at a mean distance of 1.5 million km in the anti-Sun direction.

With its ability to observe across the far infrared and sub-millimetre wavelengths (55–672 μm), *Herschel* is bridging the gap between earlier infrared space missions and ground-based facilities observing in the submilimeter range. Designed to observe the "cool and distant Universe", *Herschel*'s primary science objectives are to:

- study the formation of galaxies in the early Universe and their subsequent evolution;
- investigate the creation of stars and their interaction with the interstellar medium;
- observe the chemical composition of the atmospheres and surfaces of comets, planets and satellites in our Solar System, and
- examine the molecular chemistry of the Universe.

For this, *Herschel* is equipped with three main instruments: HIFI, PACS and SPIRE, housed in a superfluid helium cryostat. The PACS and SPIRE instruments provide broadband imaging photometry in six bands centred at 75, 100, 160, 250, 350, and 500 μm and imaging spectroscopy over the range 55–672 μm, while HIFI provides very high-resolution heterodyne spectroscopy over the ranges 157–212 and 240–625 μm.

Herschel is operated as an observatory facility designed to provide a minimum of 3 years of routine science operations, with an estimated total mission lifetime of 3.5 years. As an observatory, it is available to the worldwide scientific community, with roughly two thirds of the observing time considered "open time", allocated through standard competitive calls for observing proposals.

2 Early mission phases

Exactly one month after the launch, *Herschel*'s crycover was successfully opened and the first light images of an astronomical source (M51) were obtained with the PACS instrument, demonstrating a perfect optical performance, fully according to specifications.

Building on the experience from this PACS "sneak preview", and making use of time initially allocated to "thermal stabilisation" of the whole spacecraft, all three instruments performed their initial test observations, including SPIRE images of nearby galaxies, HIFI spectroscopy of a star forming region and PACS imaging spectroscopy of a planetary nebula. These very first attempts already provided spectacular data, and were followed by the successful completion of 2 months of "Commissioning Phase", mainly used for instrument and spacecraft functional tests, plus 3 additional months of "Performance Verification", when the different planned instrument observing modes were optimised according to the results obtained in-orbit.

As a consequence of the experience gained during this three-month period, various observing modes were declared "ready to use" in a gradual fashion leading to the start of the so-called "Science Demonstration Phase", in which small snippets of the various observing programmes were executed for verification that the users were getting what they wanted; otherwise they had to update and optimize their observing programmes.

The first "Science Demonstration Phase" observations were delivered to users on 28 September 2009 and since then all remaining observing modes have been released, adapted to in-flight circumstances. In this process, some observing modes were discarded, while some others had to be fully revamped.

This sliding transition took longer than initially expected, as HIFI became unavailable on 2 August 2009, affected by an anomaly, and was only recovered for science in April 2010. Despite this adversity,we can say that PACS and SPIRE have routinely been operated since mid-December 2009 and HIFI since mid-April 2010. At the present moment, the three instruments are being operated at full speed.

3 Early science results

In the first year of Routine Science Phase operations *Herschel* has started to do the science that it will continue doing for as long as the observatory will work. And from the very beginning *Herschel* has demonstrated that the scientific results that will be obtained will have an enormous impact on essentially all fields of astronomy, from Solar System studies to Cosmology, from the analysis of star formation, included the origin of our own Sun, to the models which describe the formation of the first galaxies in the very early days of our Universe, including the physical process that take place in the interstellar medium and the feedback material that is returned by evolved stars and make the Universe look the way it looks nowadays.

3.1 Solar System studies

One of the most interesting results obtained in the early days of *Herschel* is addressed in Fig. 1, where we can see the detection with SPIRE of the dwarf planet Makemake, the third largest dwarf planet known, with a diameter of around 1500 km. With a surface temperature of only 30 K is one of the coldest objects in the Solar System, and thus very hard to detect. By taking images 44 hours apart and subtracting the "before" and "after" image, the background sky is removed. What is left, is the positive and negative image of Makemake, showing a much fainter emission at submillimetre wavelength than model predictions (9.5 ± 3.1 mJy at 250 μm), which suggests that the object is much more complex than expected. If, as *Herschel* photometry suggests, Makemake is more reflective (i.e. has higher albedo) than we thought, it could imply that its size might not be as large as earlier derived from optical data [5].

Another interesting result obtained with *Herschel* in this field was the detection of very high levels of stratospheric carbon monoxide (CO) in the atmosphere of Neptune (Key Programme: "Water and Related Chemistry in the Solar System"; P. I. Paul Hartogh). The only explanation for this result seems to be a cometary impact that may have happened about two centuries ago [4].

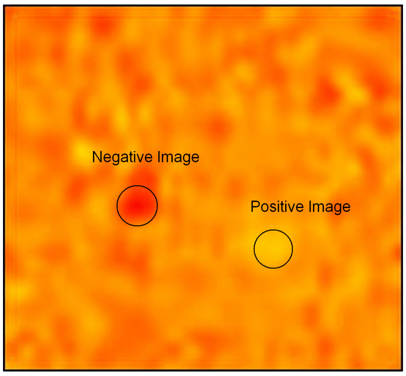

Figure 1: SPIRE differenced image of the dwarf planet Makemake (Key Programme: TNOs are cool! P. I.: Thomas Müller).

3.2 Protoplanetary disks

Herschel can also see the late stages of the formation of planetary systems like our own Solar System. Several Key Programmes have set their scientific goals in searching for extended emission around nearby stars, that may be indicative of the presence of protoplanetary disks. In some cases, Kuiper Belt-like structures have been detected by *Herschel* (see Fig. 2; [6]), made up of icy objects ranging in size from micron-sized grains to comets many kilometres in diameter.

Figure 2: The star η Corvi as seen by *Herschel*. An outer ring of icy, comet-like bodies is seen, much like the Kuiper Belt in our Solar System. This star in particular is peculiar as the system seems to contain a second warmer, dusty belt. The size of our Solar System is shown for comparison (DEBRIS; P. I.: Brenda Matthews).

3.3 New views of the Galactic plane

Hi-GAL: the *Herschel* Infrared Galactic Plane Survey, is providing spectacular images of the Milky Way demonstrating the large area mapping capabilities of *Herschel*. The survey covers a region of 120 degrees around the Galactic Center and there is the intention to expand this coverage in future open time calls to a similar area in the anti-centre region. In Fig. 3 we show one of the first tiles corresponding to this survey [7].

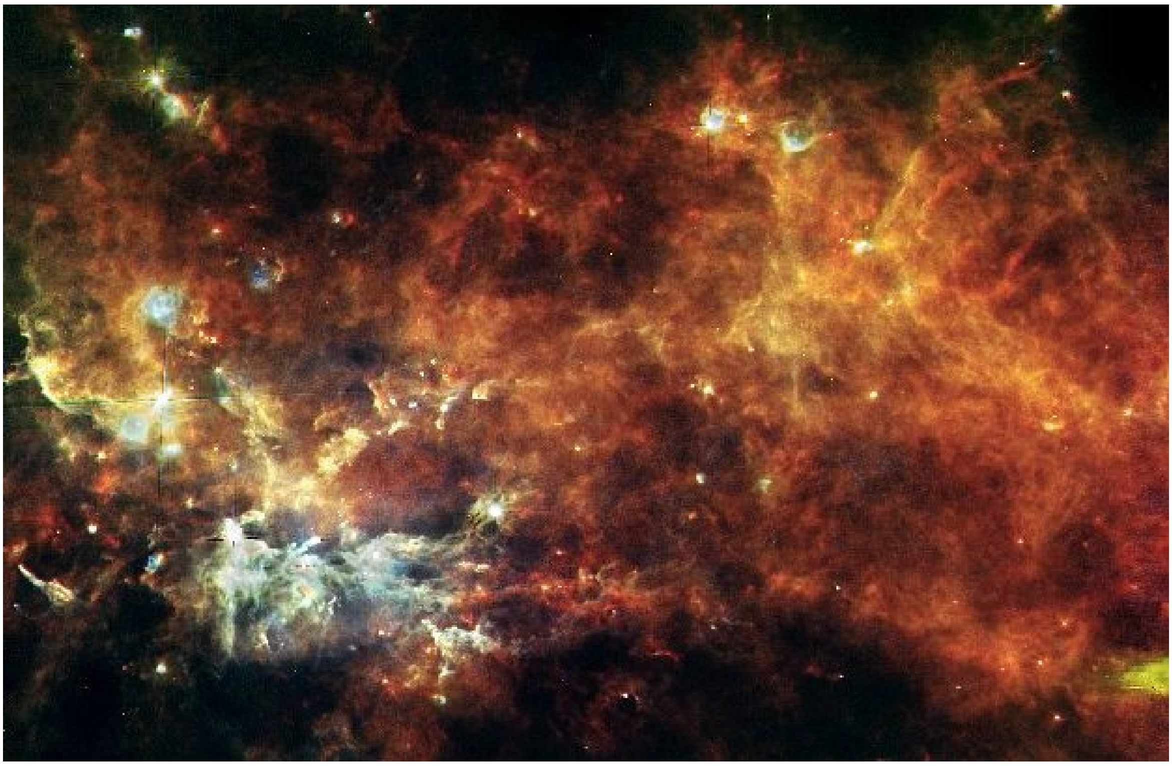

Figure 3: PACS/SPIRE three colours composite image (blue = 70 μm, green = 160 μm, red = 350 μm) which unveils our own Milky Way Galaxy around $l = 59$ deg as one giant nursery where generations of new young stars are continuously born (Hi-GAL: the *Herschel* infrared GALactic Plane Survey; P. I.: Sergio Molinari).

This image is taken in the constellation of Vulpecula and shows the entire assembly line of newborn stars. The diffuse glow reveals the widespread cold reservoir of raw material which our Galaxy has in stock for the production of new stars. Large-scale turbulence possibly due to giant colliding Galactic flows causes this material to condense into the web of filaments that we see throughout the image, and that act as "incubators" where the material becomes colder and denser.

Eventually gravitational forces will take over and fragment these filaments into chains of stellar embryos that can finally collapse to form infant stars.

3.4 Star formation

In the area of star formation *Herschel* has also contributed with the systematic mapping of some nearby star forming regions in the Gould Belt [1] and giant molecular clouds [8] which are providing us with a new view of the physical processes which lead to the formation of new stars.

The most extraordinary feature observed in all *Herschel* maps is the ubiquitous pattern of filaments in the ISM structure. The compact sources detected at 250 μm are preferentially distributed along these filaments (see Fig. 4). The high degree of association between bright filaments and dense pre-stellar cores suggests a column density threshold for the appearance of these cores, and a formation scenario that starts with the condensation of diffuse clouds into long filaments. As the column density increases, the filaments become gravitionally unstable and fragment into condensations which will become the embryos of future stars. In other less dense regions, at higher galactic latitudes, prestellar cores are located in clumps and they are not gravitationally bound, so they will likely not be able to produce new stars.

Figure 4: SPIRE and PACS images have been combined to a single composite (blue = 70 μm, green = 160 μm, red = combined SPIRE emission from all three SPIRE bands at 250/350/500 μm). The composite image easily locates the star-forming filaments that would be very difficult to isolate from a map made at a single far-infrared or submillimetre wavelength. The image contains an incredible network of filamentary structures with surprising features indicative of a chain of near-simultaneous star-formation events.

Other observations taken with *Herschel* in the vicinities of some well known OB associations show clear indications of triggered massive star formation. The observations obtained e.g. around the Rosette molecular complex [8] or RCW 120 [12] are good examples of this (see Fig. 5). With *Herschel* we can easily identify in the surrounding of ionized regions a new population of highly embedded stars which are formed in the gas and dust cocoons but are completely invisible in the optical.

Figure 5: PACS/SPIRE three colours composite image (blue = 70 μm, green = 160 μm, red = 250 μm) of the Rosette molecular complex, a good example of triggered massive star formation (HOBYS: the *Herschel* imaging survey of OB Young Stellar objects; P. I.: Frédérique Motte).

3.5 Feedback material from evolved stars

Among the results obtained in the evolved stars field by *Herschel*, the discovery of a multitude (more than 60) of spectral lines from warm water vapour in the circumstellar environment around the ageing carbon star IRC +10216 [3] with PACS and SPIRE spectroscopy is certainly one of the highlights. The results obtained by *Herschel* seem to indicate that the clumpy structure of these circumstellar shells allow UV photons from the ISM to penetrate deep enough through the envelope and trigger a set of reactions leading to the production of water.

The circumstellar shells of evolved stars are enormous molecular laboratories which allow very complex molecular chemistry; hundreds of lines are observed in some of these sources, sometimes complex organic molecules, considered to be the building blocks of life. In Fig. 6 we show, as an example, the rich molecular spectrum of the circumstellar shell around the red supergiant star VY CMa, obtained with PACS [11], an oxygen-rich star in an extreme evolutionary state that could explode as supernova at any time. The SPIRE spectrum (not shown) is dominated by prominent features coming from carbon monoxide (CO) and water (H_2O).

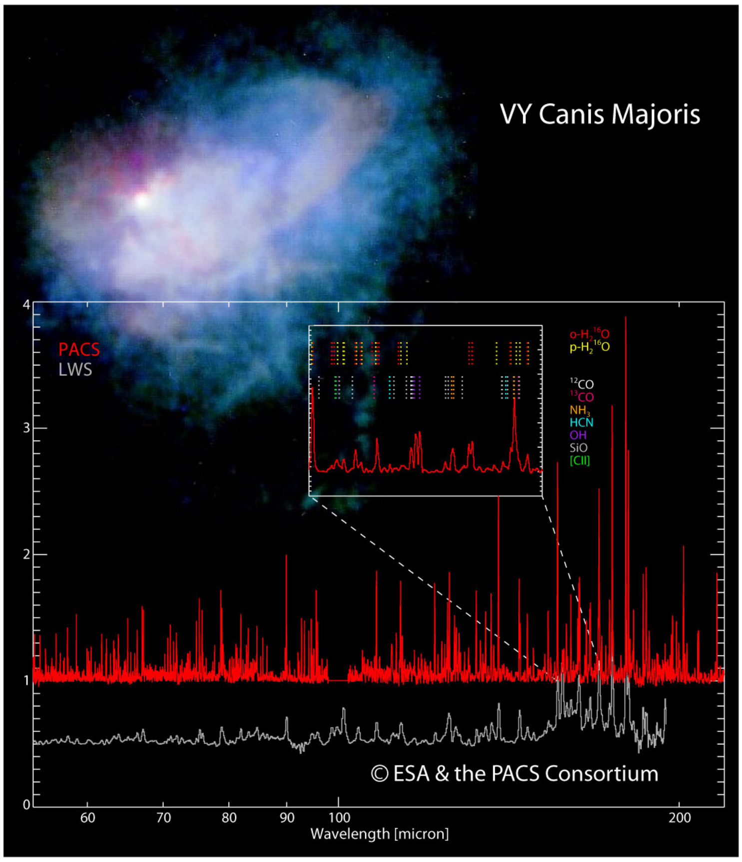

Figure 6: PACS spectrum of the red supergiant VY CMa between 57 and 210 μm. For comparison, depicted in gray, and offset by -0.5, is the observation from the ISO Long Wavelength Spectrometer (LWS). The inset shows a zoom into the 156 to 172 μm, containing 44 different identified molecular lines (MESS: Mass-loss of Evolved StarS; P. I. Martin Groenewegen).

3.6 The molecular ISM

Herschel, and in particular the heterodyne instrument HIFI onboard the spacecraft, is also ideally suited to study the physical and dynamical processes that take place in the interstellar medium between the stars, with unprecedented spectral resolution.

Some areas, like Orion, have been observed in detail with HIFI by different projects. In this region *Herschel* has obtained the most complete spectrum of molecular gas at high spectral resolution ever obtained [2], with more than 100,000 lines in one single spectrum scan (see Fig. 7). Among the organic molecules identified in this spectrum are water, carbon monoxide, formaldehyde, methanol, dimethyl ether, hydrogen cyanide, sulphur oxide, sulphur dioxide and their isotope analogues and it is expected that new organic molecules will also be identified.

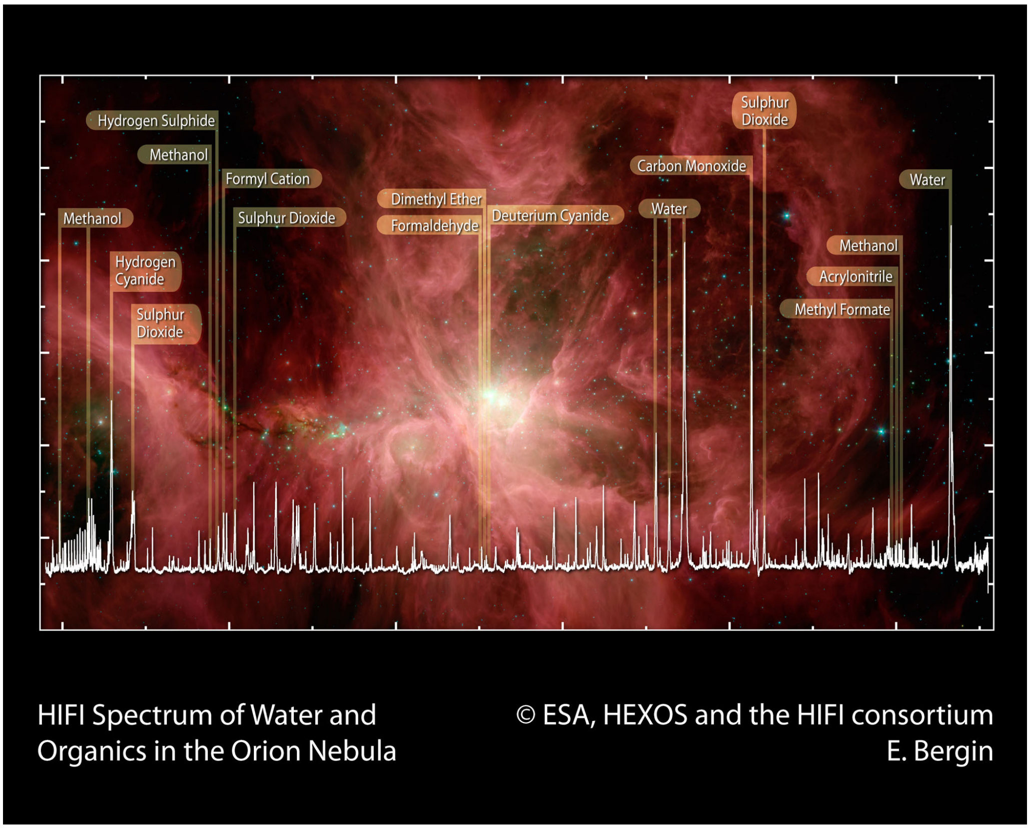

Figure 7: HIFI spectrum of the Orion Nebula, superimposed on a *Spitzer* image of Orion, showing the spectrum richness of this source (HEXOS: *Herschel*/HIFI Observations of Extraordinary Sources; P. I.: Ted Bergin).

This spectrum is just the first glimpse at the spectral richness of the kind of sources that *Herschel* will observe and it harbours the promise of a deep understanding of the chemistry of the interstellar space once this and other complete spectral surveys are available.

3.7 Extragalactic astronomy

Herschel is also providing PACS and SPIRE integral field spectroscopic data, as well as the more detailed images ever obtained of dusty nearby galaxies in the infrared and submilimeter range, together with a complete renovated view of the more distant galaxies in the Universe.

In the vicinities of our Milky Way, *Herschel*/PACS has been able to provide for the first time spatially resolved spectroscopic images of the ISM in the nearest starburst galaxy M 82. The line ratio [O III]/[C II], a diagnostic of ionized gas vs. neutral gas drops rapidly going outwards from the galaxy centre along the disk. In contrast, this ratio does not drop so significantly when going outward in the super-wind direction. On the other hand, the SPIRE spectrum of M 82 shows strong emission lines from CO over the whole spectral range, which are used to constrain the fundamental properties of the gas, as well as emission lines from atomic carbon and ionized nitrogen [9].

With the help of *Herschel* we can now study the process of star formation and nuclear activity in infrared bright galaxies at practically all redshifts. For each redshift range we can observe a larger number of galaxies and galaxies which are fainter than in any other previous studies made with other infrared telescopes in the past, like *Spitzer*. The results obtained confirm that star formation was several times more active and efficient in the early Universe, compared to the current rates of star formation.

Some *Herschel* Key Programmes are obtaining deep images of cosmological fields like GOODS North and South, the Hubble Deep Field or COSMOS (see Figs. 8 and 9), and the results obtained indicate that with *Herschel* we can now resolve more than half of the Cosmic Infrared Background (CIB) into individual galaxies. The CIB is a relic, isotropic emission distinct from the Cosmic Microwave Background (CMB) associated with the formation of galaxies. Predicted in the mid-1960s, it was first detected, only 30 years later, with the Cosmic Background Explorer (COBE). The CIB is particularly hard to probe, as all galaxies at all redshifts contribute to it and hence it has no characteristic signature. Since the CIB peaks around 100–200 μm, the majority of the galaxies contributing to this emission remained unidentified in the pre-*Herschel* era.

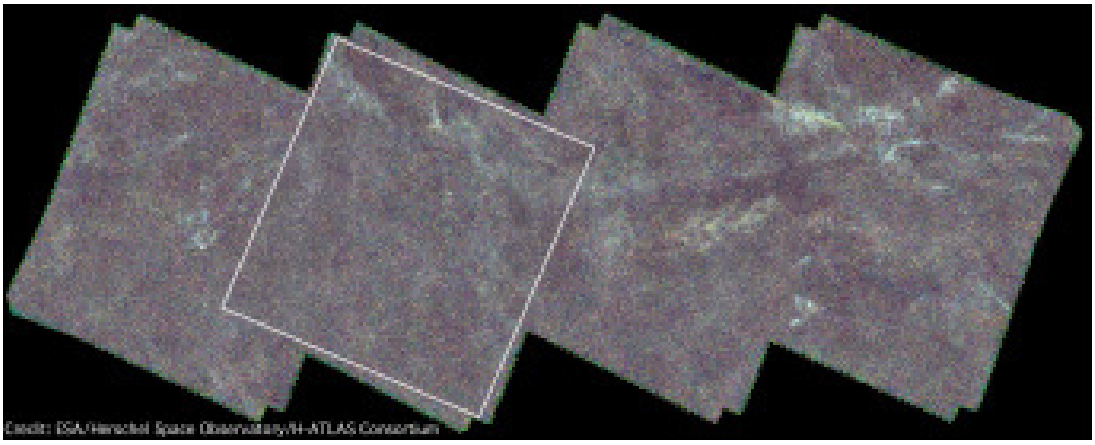

Figure 8: *Herschel*-ATLAS survey (P. I. Steven Eales) composite colour images in bands 250, 350, and 500 μm of a field covering roughly 4×4 deg on the sky (more than 60 times larger than the full moon). This took 16 hours to observe and contains more than 6,000 galaxies in the inner 14 deg^2, which represents only 2.5% of the total survey area.

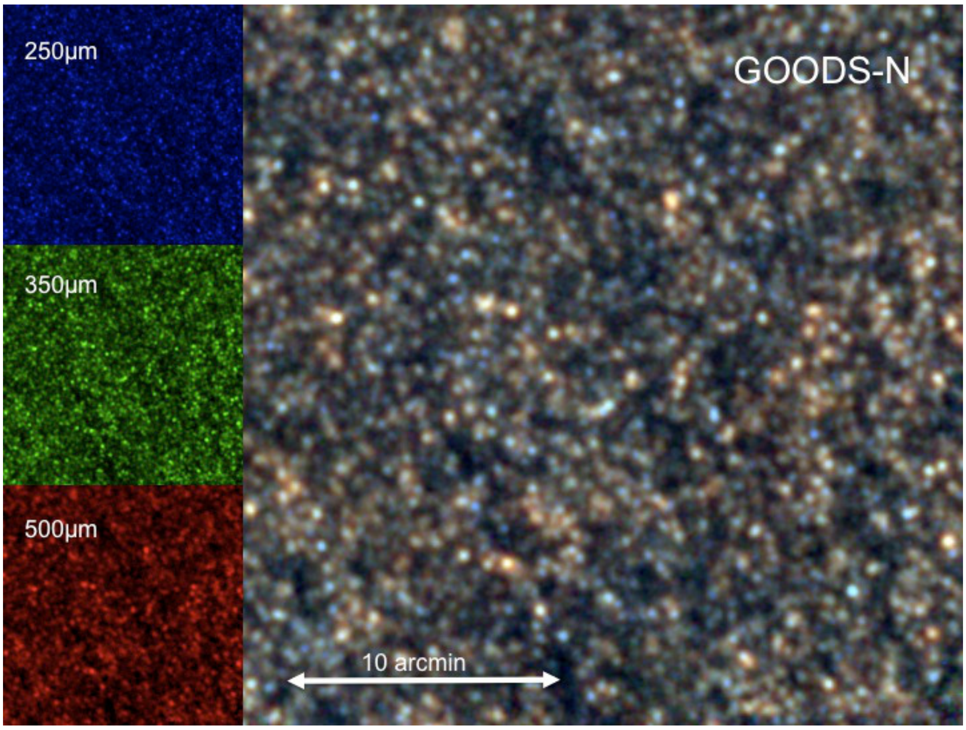

Figure 9: SPIRE image of GOODS-North, an area of sky devoid of foreground objects, such as stars within our Galaxy, or any other nearby galaxies, a little larger than the area of the full moon as observed from Earth. The image is made from the three SPIRE bands, with red, green and blue corresponding to 500 μm, 350 μm and 250 μm, respectively. The image just took 14 hours of observations. Every fuzzy blob in this image is a very distant galaxy, seen as they were 3 to 10 thousand million years ago when the star formation was very widely spread throughout the Universe (HERMES survey; P. I.: Seb Oliver).

The images obtained on these cosmological fields are providing us now with a much clearer idea of how star formation has progressed throughout the history of the Universe. Studying these galaxies at this early stage of the Universe will allow astronomers to test their models of star and galaxy formation.

3.8 ... and much more is yet to come

A lot of people all around the world have been working in the last 20 years to make this mission possible. Thanks to all of them *Herschel* is now a fully working observatory with its three science instruments working at full speed, providing plenty of new food for thought every day. Not only are the observatory and the instruments working very well, but it is already clear that in this unexplored region of the spectrum the Universe is even more interesting that we ever thought. Some of the initial findings have been put together in two special issues of *Astronomy & Astrophysics* (Vols. 518 and 521). They contain in total more than 200 refereed papers describing just the first 3 months of scientific operations with *Herschel*. This is certainly only the beginning of what *Herschel* will be able to provide us in the coming two years. *Herschel* is undoubtfully called to expand significantly our knowledge on the formation and evolution of stars and galaxies, showing us the Universe in we live as we had never seen it before.

Acknowledgments

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