NASA Herschel Science Center at IPAC

OVERVIEW WITH SCIENCE HIGHLIGHTS

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TABLE OF CONTENTS

1. The *Herschel* Mission

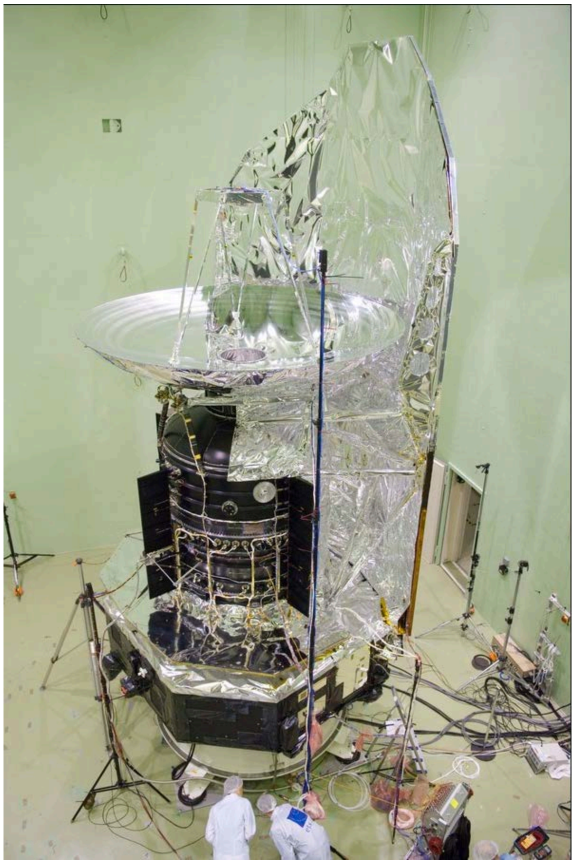


Figure 1: Herschel during final testing.

Figure 2: Launch on Ariane 5 on 14 May 2009.

1.1 *Herschel* Space Observatory

The 3.5-meter diameter *Herschel* Space Observatory (Pilbratt, G. L., Riedinger, J.R., Passvogel, T., et al., 2010), launched to L2, remains the largest space observatory to explore the full range of the far-IR and sub-millimeter to a depth and quality of detail never before realized. *Herschel* was an ESA Cornerstone mission, with significant contributions from NASA, including enabling technology for two of its three instruments. The observatory completed its 3.9-year mission on 23 April 2013 when it ran out of liquid helium. Together, all three instruments, HIFI, SPIRE and PACS, covered a wavelength range from 60 to 670 µm, and included imagers and spectrometers to both map and spectrally dissect far-IR/sub-mm emissions from space.

Additional details on the Herschel Mission and Key Programmes are provided in an SPIE presentation given in 2008 (http://herschel.esac.esa.int/Publ/2008/SPIE2008_Herschel_talk.pdf), as well as the Herschel Observers Manual (http://herschel.esac.esa.int/Docs/Herschel/html/observatory.html).

1.1.1 Heterodyne Instrument for the Far Infrared (HIFI)

HIFI (de Graauw, T. Helmich, F. P., Philips, T. G., et al., 2010) was a high-resolution heterodyne spectrometer with broad-band far-IR/sub-mm coverage over seven bands (covering 0.49 to 1.25 THz in 5 bands and 1.41-1.91 THz in 2 dual-band systems), with a spectral resolution reaching $R = 10^7$ (or up to 30 m s^{-1} velocity resolution!). The seven mixers were revolutionary in design, and reached near-quantum noise-limiting sensitivity in some of the bands. It employed Superconductor-Insulator-Superconductor (SIS) technology developed by Tom Phillips's group at Caltech/JPL, as well as Hot Electron Bolometers (HEB) developed in Sweden at the highest frequencies. A common optics design combined the seven separate beams and a beam chopper, allowing for a variety of flexible observing modes to be adopted. Although effectively a single beam instrument, maps were made of some extended sources by scanning the telescope. The intermediate frequency signals were processed either using an acousto-optical or a digital autocorrelation spectrometer back-end. The HIFI instrument team was led by Thijs de Graauw (and later Frank Helmich) based at SRON in the Netherlands, and benefited from important U.S. contributions from Caltech and JPL.

1.1.2 Spectral and Photometric Imaging REceiver (SPIRE)

SPIRE (Griffin M. J., Abergel, A., Abreu, A., et al., 2010) consisted of both an imaging photometer and an imaging Fourier Transform Spectrometer (FTS). The photometer operated over 3 bands simultaneously (250, 350 and 500 µm) in a multi-beam array covering a field of view of 4 × 8 arcminutes^2. The FTS, also multi-beamed, covered two overlapping bands in the wavelength range 191-671 µm (0.447-1.568 THz). The spectral resolution of the FTS was variable, from R = 40 to 1000 (minimum of 300 km s^{-1} velocity resolution), and the field of view of the spectrometer beam pattern was 2 arcminutes in diameter. Maps were built up by scanning the detector arrays across the sky, allowing large areas of sky to be mapped efficiently. SPIRE was developed by a consortium of European and American scientists, led by Matt Griffin at the Physics and Astronomy Department of Cardiff University, UK. The U.S. contributed the detector arrays in the form of "spider web bolometers" developed at JPL by Jamie Bock.

1.1.3 Photodetector Array Camera and Spectrometer (PACS)

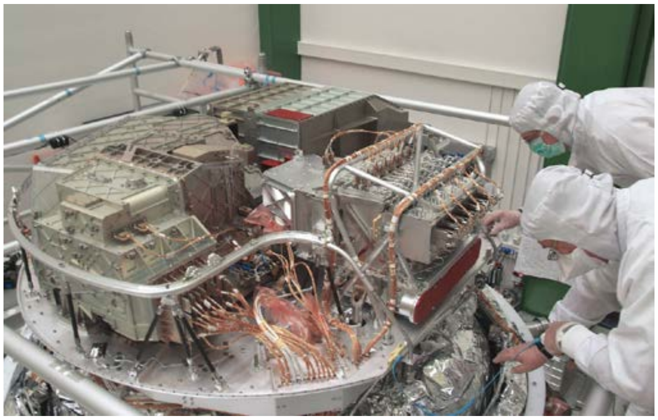


Figure 3: Integration of the *Herschel* instruments before launch. HIFI is at the front-right, SPIRE is at the back and PACS is front-left.

PACS (Poglitsch, A., Waelkens, C., Geis, N., et al., 2010) comprised of both an imaging photometer and a spectrometer, but designed to operate at shorter wavelengths than SPIRE. The photometer consisted of two filled silicon bolometer arrays with 16 × 32 and 32 × 64 pixels, respectively, and could observe with two (of three) bands simultaneously (70, 100, or 160 µm). The spectrometer employed two Ge:Ga photoconductor arrays (stressed and unstressed) with 16 × 25 pixels each to detect long and short wavelength IR radiation covering 60 µm to 210. It operated simultaneously in the red and blue using a dichroic to separate the light, imaging a 47 × 47 arcsec^2 field of view with an image slicer in a 5 × 5 pixel format projected onto the sky. The spectral resolution of the spectrometer was approximately $940 < R < 5500$, or 55-320 km s^{-1} velocity resolution. The PACS photometer and spectrometer was developed by a consortium, led by Albrecht Poglitsch, based at MPE in Munich, Germany.

2. U.S. Participation in *Herschel* Science

2.1 U.S. Instrument Contributions

NASA contributed key technology to two of *Herschel*'s three detector instruments: SPIRE and HIFI.

Spectral and Photometric Imaging Receiver (SPIRE): The U.S. provided "spider web bolometers," which were significantly more sensitive than previous composite bolometers. The bolometers were developed by Jamie Bock of JPL, SPIRE's Co-Investigator.

Heterodyne Instrument for the Far-IR (HIFI): The U.S. also provided the mixers and local oscillator chains for the two highest frequency bands, as well as other local oscillator components and power amplifiers for several other of the six bands used on the instrument. The hardware was developed at Caltech and JPL under the supervision of HIFI NASA PI Thomas Phillips.

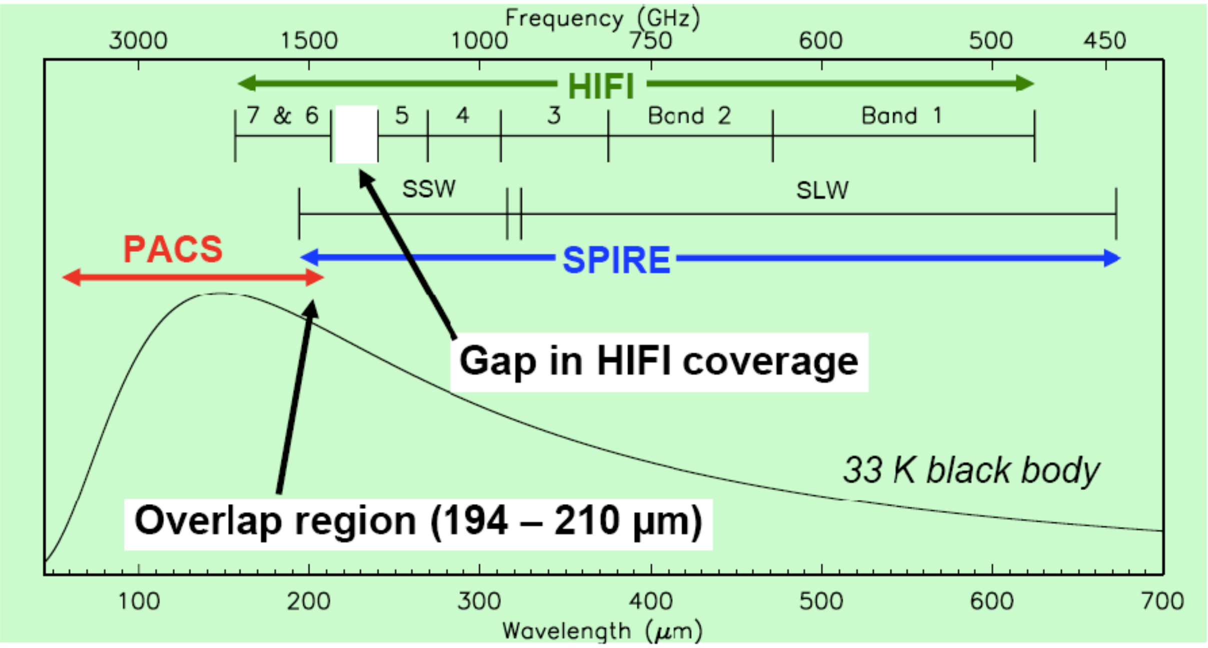


Figure 4: The wavelength and frequency range of the three *Herschel* spectrometers. Between them, they provided complete coverage in wavelength from 60-670 µm.

2.2 *Herschel* Publication Legacy

Herschel was launched on 14 May 2009, and the first publications in 2010 were dominated by two Astronomy and Astrophysics Special Features. The first was published in July 2010 (152 papers), followed shortly by a second special HIFI edition in October 2010 (50 papers). HIFI publications were delayed by a few months because of a HIFI anomaly in the first weeks of the mission that led to a re-scheduling of HIFI observations to a later time. This allowed the hardware problem to be successfully addressed, and HIFI observations resumed normally, with no issues, for the rest of the mission. Since the beginning of 2011 the rate of publications has increased, and continues to rise four years after the end of the data-collection phase of the mission on 29 April 2013, when the cryogen ran out and the detectors warmed up. The total number of *Herschel*-related refereed publications now stands at 2233 papers (July 2018). The fraction of U.S. author-contributed papers has fallen slightly from 83% per year in 2013 to 73% in 2018, but is still very high. In 2018, the paper count in July is similar to that seen at the same time in 2017, and so the publication rates do not yet seem to be slowing significantly. This is an indication of the importance of the *Herschel* archive to the astrophysics community.

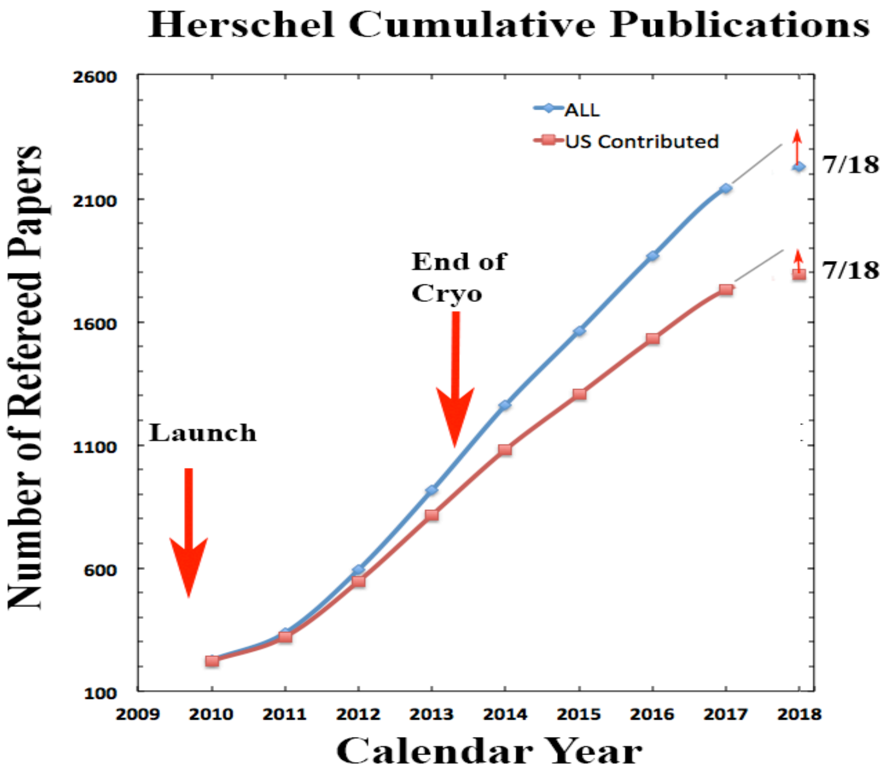


Figure 5: The cumulative refereed publication rate over the *Herschel* mission based on data obtained from the *Herschel* ADS Publication Tool (http://adsabs.harvard.edu/cgi-bin/nph-abs_connect?library&libname=HerschelPapers&libid=4c44938764) developed to monitor publications by the *Herschel* Science Center. Papers are included in the statistics if they are based on *Herschel* in-flight observations. The vast majority of the papers listed present astronomical results, and include telescope instrument performance papers based on *Herschel* archival data. Non-refereed works, conference papers, and pre-prints (e. g., arXiv.org) are specifically excluded.

We also present, in Figure 6, pie charts showing the distribution of papers by scientific topic (right panel) compared with the amount of observing time devoted to those topics (left panel). It is clear from the similarity between the two charts that publications closely track observing time for each topic, with the massive stars and local star formation in the galaxy, and research on nearby galaxies taking the largest fractions of both observation clock time and publications. More than half of the publications are on extragalactic topics, again closely tracking the amount of time allocated by the *Herschel* TAC for this kind of science.

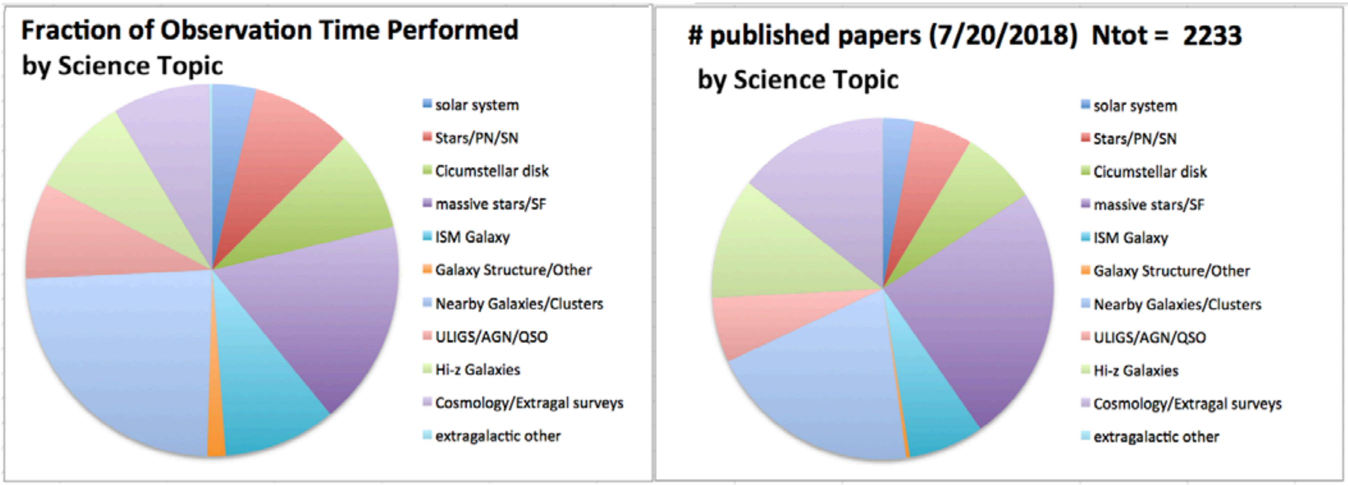


Figure 6: (Right) A pie chart showing the distribution of papers by scientific topic, compared with (Left) the amount of observing time devoted to those topics.

Figure 7: The NASA *Herschel* Science Center, located at IPAC on the California Institute of Technology campus in Pasadena, California.

3. Overview of the NASA *Herschel* Science Center

3.1 NHSC Charter

The NASA *Herschel* Science Center (NHSC) was created at the Infrared Processing and Analysis Center (IPAC) on the Caltech campus in Pasadena, California as part of the NASA participation in Herschel. The NHSC operated throughout the lifetime of the *Herschel* project from 2001 to 2018. Its main goals were embedded in the Charter, which stated the NHSC would:

- ensure the necessary resources and tools are available to the U.S. scientific community to take advantage of the scientific capabilities of the observatory in a timely manner,
- ensure availability of *Herschel* science data for U.S. archival research on timescales equivalent to ESA,
- act as an interface between the ESA *Herschel* Project and the U.S.-based scientific user community,
- advocate U.S. community needs with the HSC and ESA project,
- provide the U.S. astronomical community with technical support throughout all phases of the *Herschel* mission, from pre-launch through to the transition to archival phase, and
- manage the NASA data analysis funding for the U.S. user community.

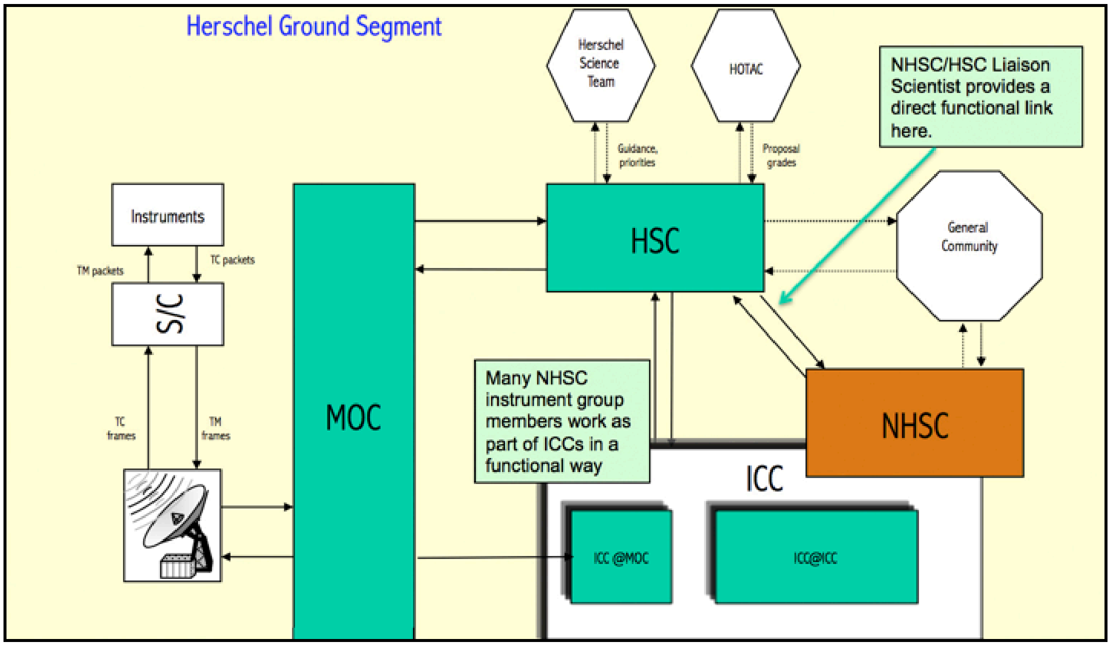


Figure 8: This illustration shows the way the NHSC interfaced with the rest of the *Herschel* Project Ground Segment. The left side of the diagram shows a schematic representation of the *Herschel* spacecraft and its interface with the Mission Operations Centre (MOC) based in Germany. The HSC, based at ESAC in Spain, and the ICCs (based in several countries) worked closely with MOC during the mission.

Building on experience at IPAC with ISO, it was decided it was important that NHSC science and technical staff should be closely integrated into efforts underway in Europe to build the science ground system and the three main instruments: HIFI, PACS, and SPIRE. The rationale was that NHSC staff would learn about the mission and the *Herschel* Ground Segment by working with the teams building them while contributing to the effort. As a result, NHSC scientists and engineers were embedded from an early time, into the newly formed European Instrument Control Centres (ICCs) in the Netherlands (HIFI), Germany (PACS) and the UK (SPIRE). This was a natural development for HIFI and SPIRE because of significant U.S. involvement in the construction of detectors and instrumentation. Even though the PACS instruments did not involve U.S. hardware, PACS leadership welcomed the same model, and NHSC staff became integrated into the PACS ICC, eventually playing important roles in pre-flight testing, software development, testing and validation of data products through the mission.

3.2 The Formation of the NHSC

In the first years (2001-2004), the initial build-up of the IPAC *Herschel* effort was performed jointly with plans to develop a *Planck* Data Analysis Center, and involved a close collaboration with NASA headquarters and the Jet Propulsion Laboratory (JPL). In addition to NHSC on the Caltech campus, the project office for *Herschel* and *Planck* had been set up earlier at JPL, and included the position of JPL Herschel Project Scientist (positions occupied over the years by strong advocates for the *FIRST/Herschel* mission: Bill Langer, Hal Yorke, and Paul Goldsmith).

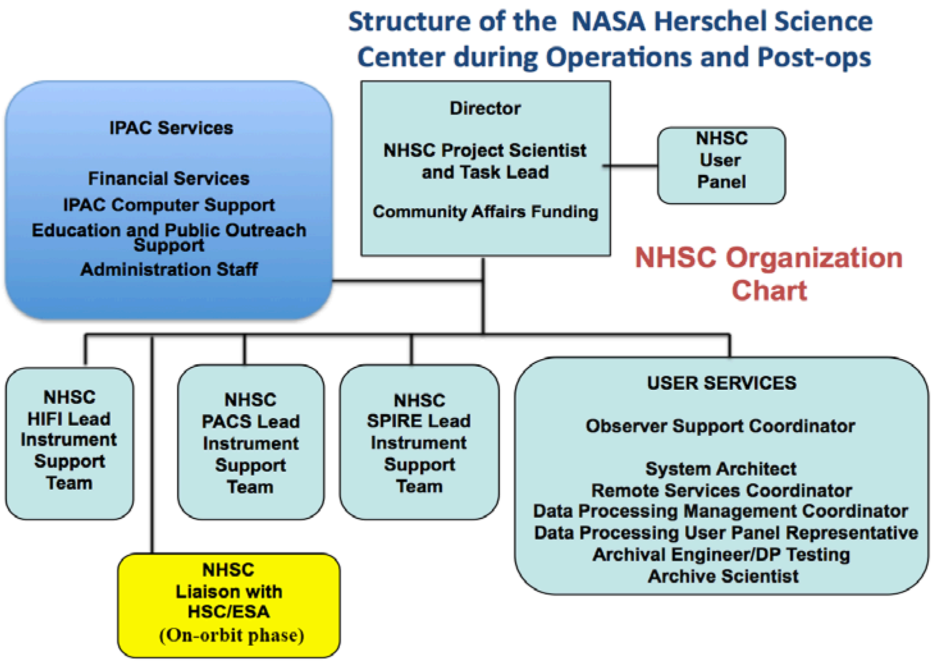


Figure 9: The structure of the NHSC during the mid- and late stages of the mission. The NHSC had three small teams, each associated with the Herschel instruments PACS, SPIRE and HIFI, and a team responsible for User Services.

The very early local efforts of laying the groundwork for what would become the NHSC were led by Steven Lord and Kenneth Ganga, under the guidance of the IPAC Director George Helou. This involved building a robust collaboration with ESA's *Herschel* Science Centre (HSC) and Instrument Control

Centres (ICCs), preparing for U.S./European technical exchanges, and developing plans for pre-launch and science workshops in Europe and the U.S. Plans were also underway for local infrastructure to provide U.S. community support, including a U.S. Helpdesk, software tool development, and IR background and confusion estimation tools accessed through a web server. The HSC decided to adapt the observation planning tool used by *Spitzer* (Spot) for use with *Herschel*, eventually turning it into HSpot with help from the IPAC experts. Supporting work on the *Herschel* Common Software System (HCSS) was also undertaken, including use case studies, requirements, and testing of suitable Java libraries. IPAC scientists also developed data reduction software, and provided laboratory data analysis associated with the early testing of SPIRE bolometers being developed at JPL by Jamie Bock, and HIFI mixers being developed by Tom Phillips on the Caltech campus.

Figure 10: Group photo of a large subset of the NHSC staff about two years prior to launch (left to right): Jeff Jacobson, Phil Appleton, George Helou, Dario Fadda, Bill Latter, Mary Ellen McElveney, Jonathan Kakumasu, Babar Ali, Pat Morris, John Rector, David Frayer, Lijun Zhang, Steve Lord, Bernhard Schulz, Joan Xie, Kevin Xu, and Nanyao Lu.

In late 2004, the NHSC went officially “live” to the U.S. community, with the opening of a community helpdesk. NHSC initially had a small staff with scientists that began to prepare the way for U.S. community engagement, and to interface with the European instrument teams. The *Herschel* Science Center, part of ESA’s European Space Astronomy Centre, near Madrid Spain, agreed to host a member of the NHSC “on-site” during the on-orbit phase of the mission to act as a liaison between the U.S. and ESA centers. This close involvement of the NHSC scientists and engineers in the early development of the *Herschel* project provided the U.S. community with local expertise on all aspects of the *Herschel* project and *Herschel* Ground Segment. It was also very much to the mutual benefit of the project as whole, since the ICCs benefited from the additional workforce, and the NHSC received needed expertise. By 2009 and throughout the rest of the project, the NHSC grew to include a small Community Support team and scientists and software engineers who interfaced with each of the three European instrument teams.

The NHSC benefited from strong input from a six-person NHSC User Panel (NUP), made up of scientists from the U.S. community. The NUP advisory meeting was held in January 2008 for a launch readiness review and continued to meet regularly throughout the mission.

4. Science Highlights on the *Herschel* Mission

This section describes science highlights primarily driven by highly cited papers led by U.S. investigators during the *Herschel* mission. A brochure describing the overall Herschel Mission and its Science Objectives can be found at https://irsa.ipac.caltech.edu/data/Herschel/docs/BR-262_Herschel_brochure_v42.pdf.

4.1 Raw Material Needed for Planetary Formation in the Proto-planetary Disk Around Nearby Star TW Hydrae

In a pioneering paper published in the journal *Nature* (Bergin, E. A., Cleves, L. I., Gorti, U., et al., 2013), a team of astronomers used the PACS spectrometer to directly detect a form of molecular hydrogen (HD), in the closest (180 light years), best studied, dusty disk around a nearby star TW Hydrae. HD is deuterated molecular hydrogen (deuterium, D, replaces one of the hydrogen atoms in the more common HH molecule), and was used to measure the mass of molecular gas much more accurately than previous techniques. Earlier observations (Hogerheijde, M. R., et al., 2011) had led to a huge range of possible masses for the disk, making it very difficult to determine whether proto-planetary disks are capable of forming planetary systems like our own. By exploiting the pure rotational transitions of the HD and another common OH molecule, both of which emit energy in the far-IR, the team led by scientists at the University of Michigan, discovered strong emission-lines from the disk. They showed that within a radius of 100 Astronomical Units (2.5x distance to Pluto in our Solar System), the dusty disk has a mass of at least 5-6% of that of the Sun. This discovery shows that TW Hydrae contains many times the amount of gas needed to make all the planets in our solar systems. Clearly these debris disks have the potential to

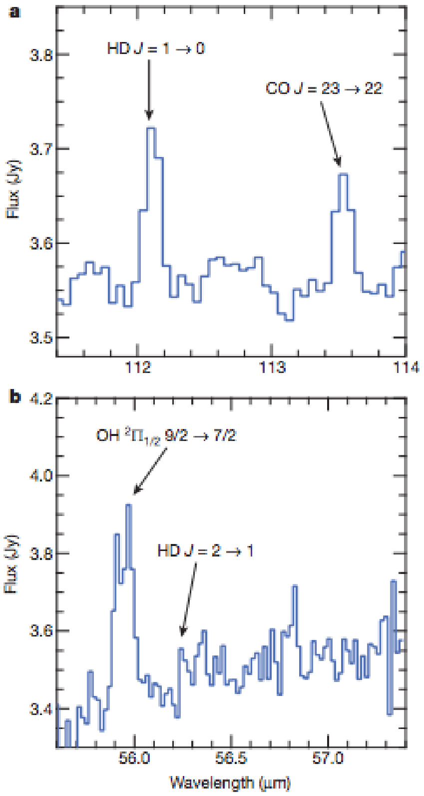


Figure 11: (Top) *Herschel* detection of the HD molecule in the TW Hydra proto-planetary disk by Bergin et al. (2013). The top panel shows the J=1-0 line of HD as well as the high J CO J = 23-22 transition from warm molecular gas. (Bottom) Simultaneous observations of the HD J = 2-1 line and OH emission at shorter wavelengths.

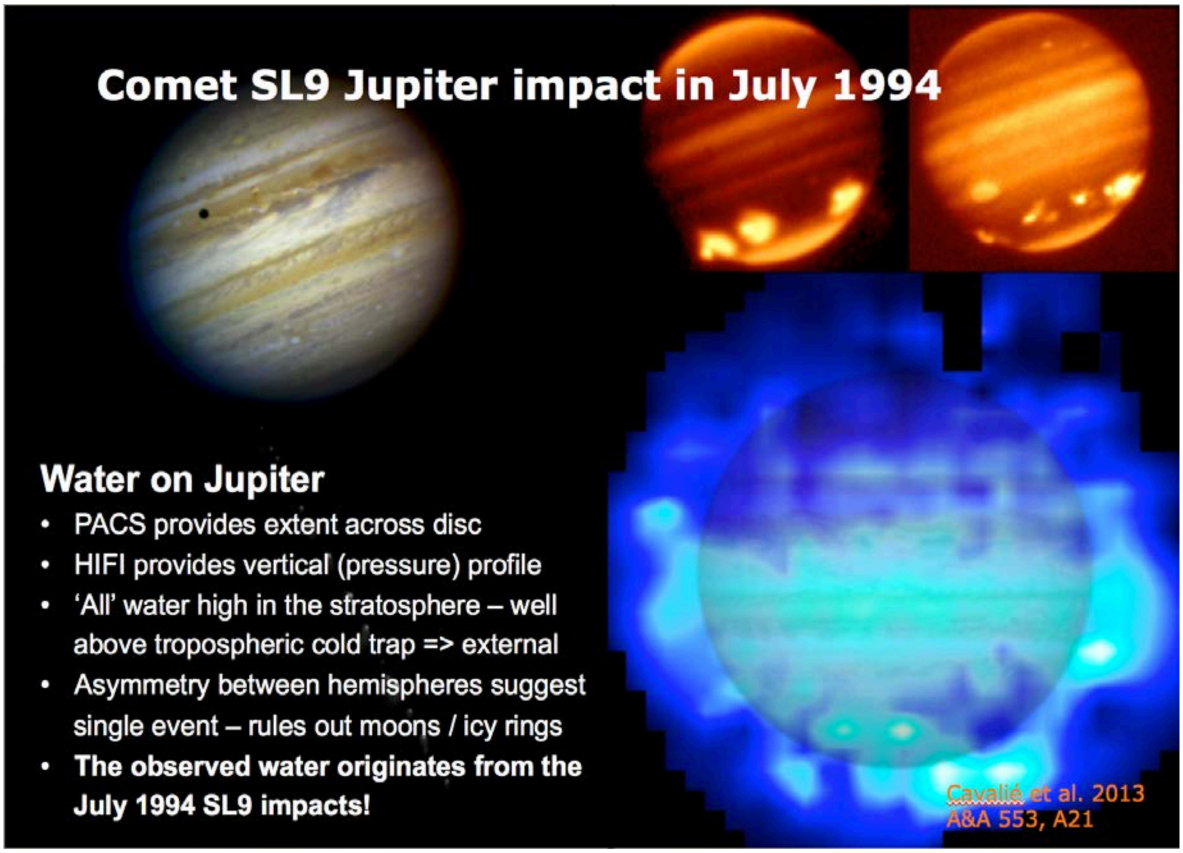
http://sci.esa.int/herschel/59494-the-cosmic-water-trail-uncovered-by-herschel/

make planets. What is especially significant is that despite TW Hydrae being relatively old, it has managed to hold a huge amount of raw material for planetary formation. *Herschel*-HIFI also was also instrumental in the discovery of cold water in TW Hydrae, and the combined results of the two papers suggests the disk may contain many thousands of times the mass of the Earth's oceans. This suggests a proto-planetary disk may be a plausible source of water on planets like the Earth.

4.2 Discovery of Earth-Ocean-like Water in Some Comets: The Origin of Earth's Oceans?

Continuing the theme of water in the Solar System, in another paper published in the journal *Nature* (Hartogh, P., Lis, D. C., Bockelée-Morvan, D., et al., 2011), a European and U.S. team detected strong sub-mm lines of water from the Jupiter family comet 103P/Hartley 2 with the *Herschel* HIFI instrument. The emission lines detected were significant for the origin of water on Earth because they included measurements of HDO (heavy water) and the rare O^{18} isotope of water (H_2O^{18}). The advantage of H_2O^{18} is that it does not suffer from spectral self- absorption, and can be used to provide a very accurate estimate of the amount of normal isotopic water in the comet. The detection of the two lines together allows the fractional abundance of deuterium to hydrogen (D/H) ratio in the comet to be measured. Water in the Earth's oceans has a very specific deuterium abundance relative to hydrogen (0.156%). Previous measurements from comets originating far out in the Solar System (the so-called Oort cloud comets), were found to have discrepant deuterium ratios compared with the Earth—ruling those comets out as a source of water for the Earth. However, the new *Herschel* results showed that 103P/Hartley 2 has an Earth-like deuterium abundance. Unlike the previous HD comets studied, 103P/Hartley 2 originates in the much less distant "Kuiper Belt," a population of comets whose orbits populate the regions between the orbit of Neptune and Pluto. Comets in the Kuiper Belt with similar properties to 103P/Hartley 2 could conceivably have collided with the Earth in the past, bringing with them water of the correct deuterium abundance. The new results show that Earth-like water could potentially have been supplied to the Earth in the past by frequent collisions with an abundance of comets perturbed from the Kuiper Belt into the inner Solar System by the action of the outer planets.

Another important discovery (Cavalié, T.; Feuchtgruber, H.; Lellouch, E. et al., 2013) relating to the importance of comets as carriers of water was made with both the *Herschel* HIFI and PACS spectrometers. Observations of Jupiter were made that conclusively detected water across the face of the planet. The water is believed to be the lasting result of the collision between the comet Shoemaker-Levy 9 and Jupiter in July 1994. These observations were made in December 2009 with *Herschel*, 15 years after the SL-9 collision with Jupiter.



Comet SL9 Jupiter impact in July 1994

Water on Jupiter

- PACS provides extent across disc
- HIFI provides vertical (pressure) profile
- 'All' water high in the stratosphere – well above tropospheric cold trap => external
- Asymmetry between hemispheres suggest single event – rules out moons / icy rings
- **The observed water originates from the July 1994 SL9 impacts!**

Cavalié et al. 2013
A&A 553, A21

Figure 12: (Top-left) Image of visible disk of Jupiter before the impact of the comet fragments of Shoemaker-Levy 9, and near-IR images (top-right) showing the impact sites shortly after the collisions. (Bottom-right) A PACS image (derived from a full spectral map) at 66.4 µm of water emission (blue) superimposed on the disk for clarity. The water, most likely deposited in Jupiter's atmosphere by the comet, has remained there since the SL-9 impacts.

4.3 The Birth of Stars in Molecular Filaments and the Origin of Organic Molecules

Early in the *Herschel* mission, using images from *Herschel*'s PACS and SPIRE photometers, it was discovered that dusty filaments are ubiquitous throughout the Milky Way, and these filaments are the source of low-mass star formation in the galaxy (André, P., Men'shchikov, A., Bontemps, S., et al., 2010). Hundreds of pre-stellar cores and Class 0 proto-stars were quickly correlated with complex networks of dusty filaments.

Water has long been known to be an important constituent of the gaseous medium between stars, but until *Herschel*, it was not known how water forms in space. In 2010, two U.S.-led teams (Gerin, M., de Luca, M., Black, J., et al., 2010) (Neufeld, D. A., Goicoechea, J. R., Sonentrucker, P., et al., 2010), using the HIFI instrument on *Herschel*, observed the key ingredients of the chemistry that leads to the formation of interstellar water; namely the highly reactive "molecular ions" OH^+, H_2O^+, and H_3O^+. These species play a critical role in the formation of stable water molecules through complex chemical reactions. Both teams showed that water forms in warm interstellar clouds through a set of chemical reactions starting with ionized hydrogen and molecular hydrogen excited by cosmic rays. Cosmic rays are notoriously difficult to quantify throughout the galaxy, and their origin is still shrouded in mystery. However, as a spin-off, the observations provided an accurate way of measuring the cosmic ray ionization rates throughout the galaxy, and potentially other galaxies.

Indeed, later in the *Herschel* mission, another team of U.S. astronomers (González-Alfonso, E., Fischer, J., Bruderer, S., et al., 2018) (González-Alfonso, 2018) were able to use the detection of OH^+ and H_2O^+ in an outpouring of gas from the nearest quasar. The results show that cosmic rays, excited by repeated shocks, were responsible for creating a large flow of ions from this Active Galactic Nucleus (AGN) powered by a supermassive black hole. This is the topic of the next major discovery of *Herschel* in the area of molecular outflows from galactic nuclei.

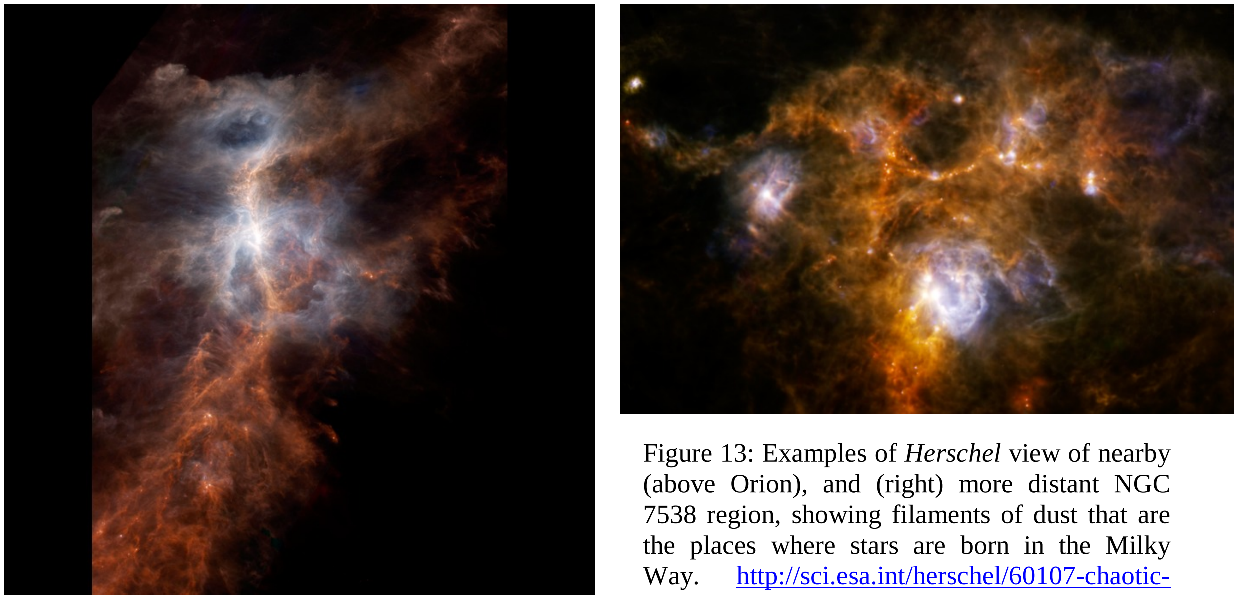


Figure 13: Examples of *Herschel* view of nearby (above Orion), and (right) more distant NGC 7538 region, showing filaments of dust that are the places where stars are born in the Milky Way. http://sci.esa.int/herschel/60107-chaotic-web-of-filaments-in-a-milky-way-stellar-nursery/

4.4 Molecular Outflows from Ultra-luminous Infrared Galaxies and Active Galactic Nuclei

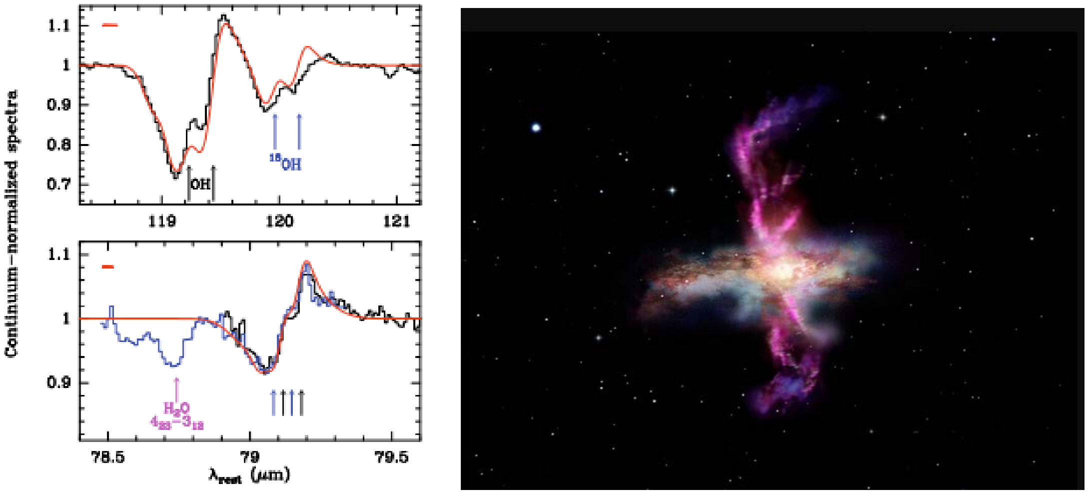


Figure 14: (Left) The far-IR spectrum of Mk 231 observed with the PACS spectrometer showing strong OH emission and absorption in a typical P-Cygni profile, commonly seen in stars with outflowing gas. The similar profile for this galaxy suggests large quantities of molecules are escaping the galaxy; see artist’s realization on (Right). Two separate transitions of OH, as well as “warm” water (i.e., steam), is seen flowing out of the galaxy.

A major discovery of the *Herschel* mission was the detection of very large outflows of molecules from the nuclei of galaxies using the PACS spectrometer. The first paper in a series of discoveries was presented by a U.S. first author (Fischer, J., Sturm, E., González-Alfonso, E., et al., 2010) showing OH^+ and H_2O^+ molecular gas streaming out of the nucleus of the local ULIRG, Mrk 231, with a velocity of at least 1400 km/s, and an outflow mass of more than 70 million solar masses of gas. This initial paper was quickly followed by more similar observations of galaxies containing AGN (containing supermassive black holes), and less energetic outflows from starburst galaxies (where the energy source is likely to be winds and supernovae). (Sturm, E., Gonzalez-Alfonso, E., Veilleux, S., et al., 2017) (Veilleux, S., Meléndez, M., Sturm, E., et al., 2011) (Rangwala, N., Maloney, P. R., Glenn, J., et al., 2011) These PACS results were followed by an avalanche of results from the SPIRE Fourier-Transform Spectrometer (FTS), providing an unprecedented view of molecular gas both within, and outflowing from, ULIRGs like Arp 220. These huge outflow rates significantly exceed the star formation rates in these galaxies, suggesting the process being observed must quickly deplete the galaxy of fuel and shut off star formation.

4.5 Fundamental Properties of Dust in Nearby Galaxies

In several seminal, highly-cited U.S.-led papers (Dale, D. A., Aniano, G., Engelbracht, C. W, 2012) (Sandstrom, K. M., Leroy, A. K., Walter, F., et al., 2013), *Herschel* has been able to extend the work done by *Spitzer* to the longer wavelengths where the Spectral Energy Distributions (SEDs) of galaxies peak in the far-IR. In the case of the KINGFISH (Kennicutt, R. C., Calzetti, D., Aniano, G., et al., 2011) survey of 61 nearby galaxies, astronomers were able to show we have been underestimating the amount of dust in galaxies by a factor of two, because single temperature black-body curves assumed previously did not capture the true range of dust temperatures found when the full SED is explored.

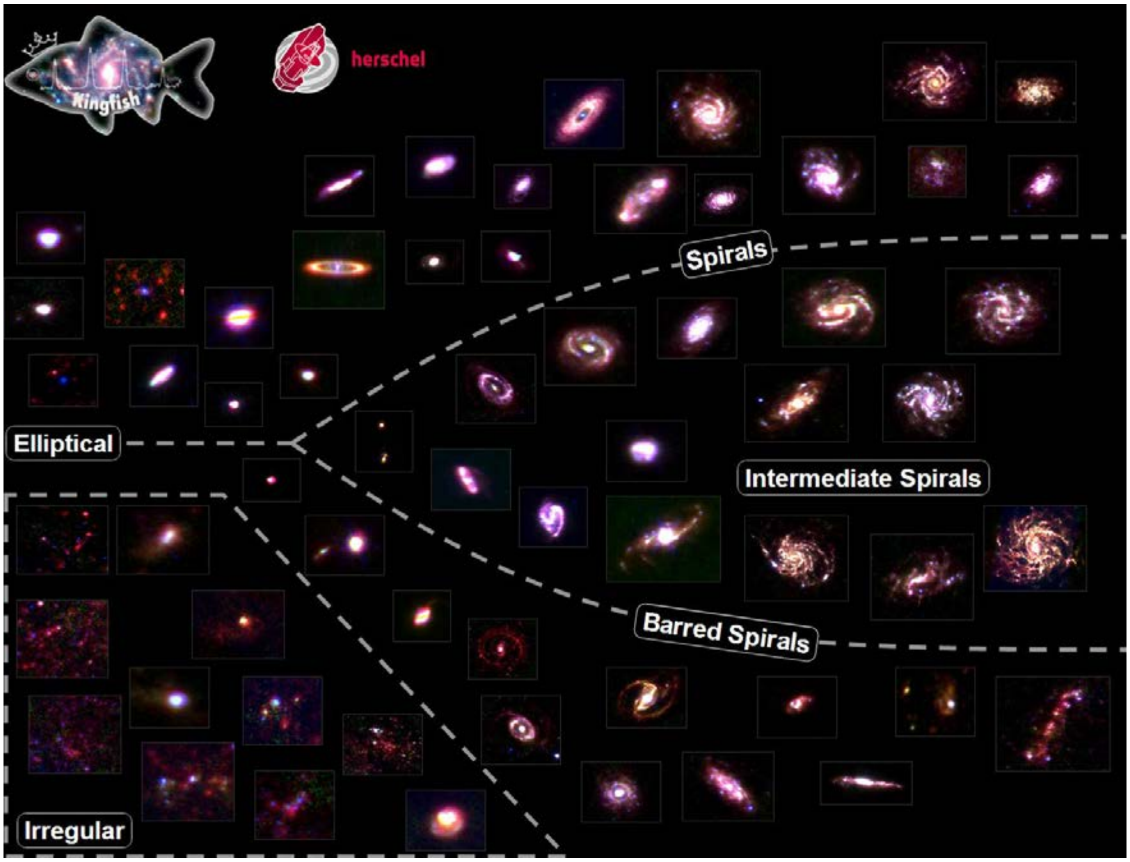


Figure 15: An infrared version of the famous “Hubble tuning-fork” diagram that is commonly used to describe the different kinds of galaxy morphologies found in the local Universe. Unlike the classical tuning-fork diagram, which showed visible light images, this one shows infrared images, taken with *Herschel*, of the Elliptical galaxies (left) and the two prongs of the tuning fork (upper prong Spiral Galaxies and low prong, Barred Spirals). Interestingly, the IR images, which are sensitive largely to dust rather than Hubble’s original visible (mainly stellar) distributions of light, show strikingly similar trends from left to right, going from smooth-dust ellipsoidal galaxies to increasingly clumpy dust clouds in the disks of the spiral galaxies. This emphasizes the close connection between stars and the interstellar medium from which they have formed and evolved. From the KINGFISH project (Kennicutt, R. C., Calzetti, D., Aniano, G., et al., 2011).

The KINGFISH project was also able to provide the most accurate measurement of a very useful quantity often used to measure the total gas mass in galaxies. This quantity, X_{co}, is the ratio of the intensity of carbon monoxide (CO) emission to the total molecular hydrogen mass. The reason why X_{co} is important is because CO observations (obtained from ground-based radio telescopes) tend to be the most easily available measured quantities of molecular gas in galaxies, even out to high redshifts. Often the CO emission is observed, and the value of X_{co} is commonly assumed, despite being very uncertain, to obtain the total molecular hydrogen mass. In this U.S.-led KINGFISH paper, a more accurate measurement of X_{co} was determined by simultaneously solving for both X_{co} and the gas-to-dust ratio in a sample of 782 normal galaxies using *Herschel* photometry and ground-based CO measurements. In addition to showing that, for normal galaxies, X_{co} had a narrow range, the work showed how properties X_{co} and the gas to dust ratio changes with heavy element abundance in the galaxies.

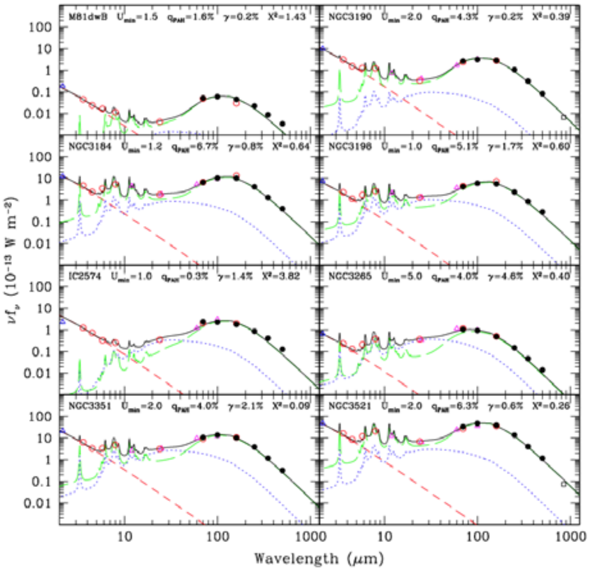
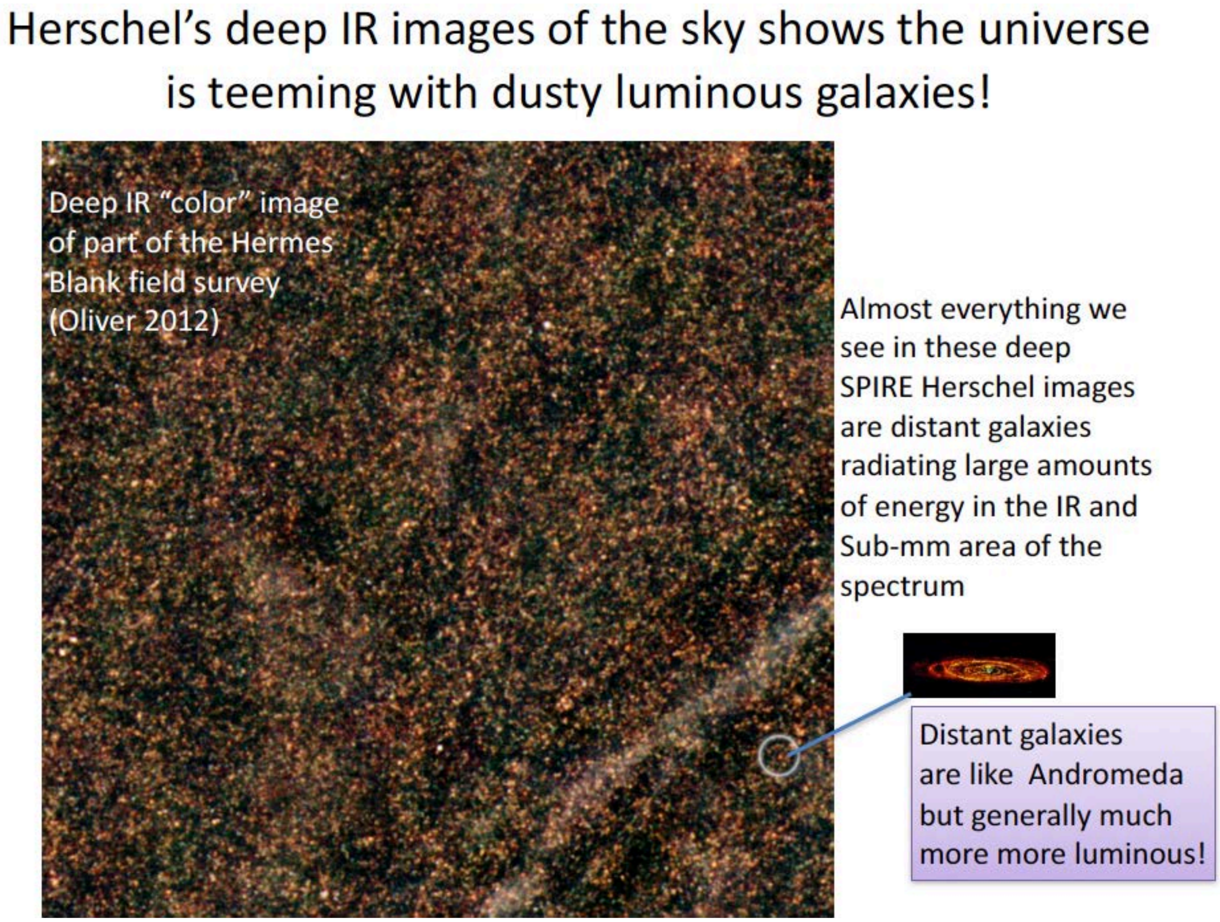


Figure 16: Infrared spectral energy distributions showing the infrared energy as a function of wavelength for a few of the galaxies observed in the KINGFISH nearby galaxy survey. Such plots allow astronomers to estimate the importance of difference sources of emission in the galaxies, from stars to warm and cold dust. From such diagrams it was possible to estimate the mass of dust in each galaxy. This could be compared with molecular line observations to estimate the gas to dust ratio.

4.6 *Herschel* and Galaxy Evolution

Herschel's deep sky surveys showed that almost everything detected in the far-IR and sub-mm are galaxies spread spatially over the sky and over a large range of cosmic volume and time. Images of the sky with *Herschel* look like grains of sand on the beach, with each "grain" being a separate galaxy. *Herschel*, unlike previous IR missions, was able to measure the radiant energy from galaxies over a huge range of IR and sub-mm wavelengths—allowing a true measure of the far-IR power from galaxies to be properly accounted for. These measurements allowed astronomers to determine the changes in star formation rates and dust temperatures to much higher redshifts (deeper into space, and further back in time, the so-called "look-back time") than had been previously possible. We can now conclusively state the galaxy star formation rate per unit volume of space was approximately ten times larger 10 billion years ago (redshift = 2), compared with the local Universe. Understanding why is central to the field of galaxy evolution.



Herschel's deep IR images of the sky shows the universe is teeming with dusty luminous galaxies!

Deep IR "color" image of part of the Hermes Blank field survey (Oliver 2012)

Almost everything we see in these deep SPIRE Herschel images are distant galaxies radiating large amounts of energy in the IR and Sub-mm area of the spectrum

Distant galaxies are like Andromeda but generally much more more luminous!

Figure 17: A deep, multi-color image of the Hermes deep field made with SPIRE (Oliver, S. J., Bock, J., Altieri, B., et al., 2012).

4.6.1 The Galaxy "Main Sequence"

In an important paper that includes significant U.S. co-authors (Elbaz, D., Dickinson, M., Hwang, H. S., et al., 2011) and using observations from the GOODS-*Herschel* key program, it was convincingly shown that star-forming galaxies follow an infrared "main sequence" that appears (nearly) universal over all redshifts and luminosities.

The galaxy "main sequence" is a relatively tight relationship between a galaxy's IR luminosity (which measures star formation rate) and it stellar mass (measured by the stellar 8 μm continuum by *Spitzer*) over a wide range of masses and IR luminosities. Not only does the main sequence relationship hold at low-redshifts (local space), but the same basic relationship works at higher redshift, with a shift in the normalization to account for the much higher average star formation rates seen at higher-z. Outliers from this main sequence are a minority of the population (<20%) at all redshifts, and are shown to consist of starbursts with star formation occurring in very compact regions. What is remarkable is that this apparent tight relationship between star formation rate and stellar mass holds over large look-back times in the Universe. This may suggest that some kind of common fine-tuning mechanism is operating to regulate gas inflow and outflow rates, and star formation rates in most galaxies over all of cosmic time, and over a wide range of masses. During the mission, more observations of larger samples have only helped to consolidate these results, although there is an indication that, at the largest galaxy masses, the main sequence relationship may flatten, although this is still controversial (Lee, N., Sanders, D. B., Casey, C. M., et al., 2015).

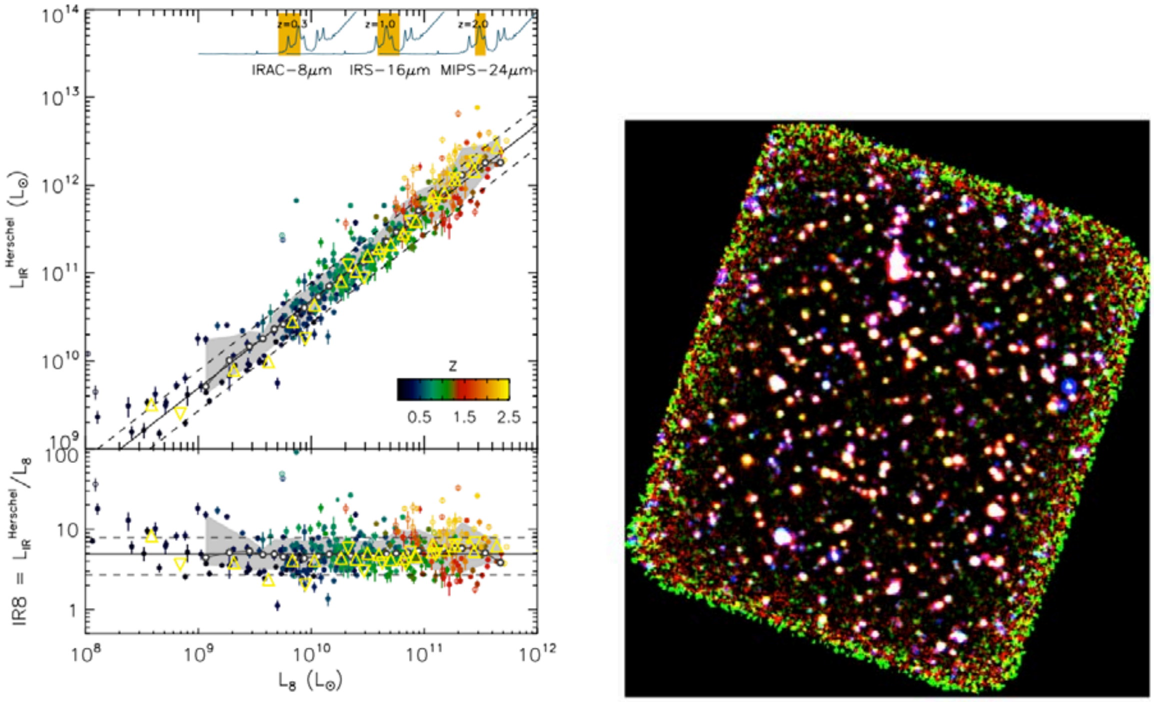


Figure 18: (Left) The tight relationship between Infrared Luminosity (proportional to star formation rate) and Stellar Mass (proportional to the IR luminosity at a rest wavelength of 8 μm), put on a firm footing by *Herschel*, is called the “Galaxy Main Sequence.” (Right). Deep *Herschel* surveys, like the GOODS North field, provide the best estimates of the total star formation rate in galaxies over a wide range of look-back time. (The look-back time is the time it takes light from a galaxy to reach the Earth from its distant staring point—often measured in billions of years for typical galaxy surveys).

4.7 *Herschel* Discovers Dust-obscured Starburst Galaxies in the High-z Universe

Herschel was able to map large areas of sky quickly with its IR cameras. As a result, it was able to discover examples of the most luminous galaxies in the Universe. These rare galaxies, which lie far above the galaxy main-sequence, are forming stars at more than 1000 M-sun per year (more than 1000x that of a normal nearby galaxy). A perfect example is the U.S.-led discovery of a z = 6.34 ultra-red galaxy, found by searching for the most extreme red galaxies in the *Herschel* HerMES survey (Riechers, D. A., Bradford, C. M., Clements, D. L., et al., 2013). These observations were followed up using many ground-based facilities, including radio and millimeter interferometers capable of detecting molecules and atomic gas (Fu, H., Cooray, A., Feruglio, C., et al., 2013) (Dowell, C. D., Conley, A., Glenn, J., et al., 2014). At such a high redshift, the Universe is only 880 Myrs old, and so the discovery of a starburst system with hundreds of billions of solar masses of highly excited, chemically enriched gas was unprecedented. A galaxy like this, forming so soon after the Big Bang and producing stars at such a frantic rate, represents a serious challenge to models of galaxy formation.

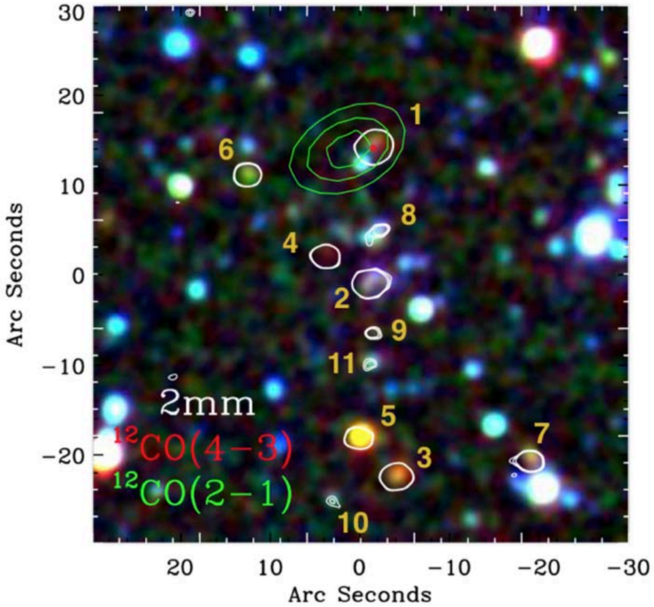


Figure 19: The *Herschel* source dubbed “Dusty Red Cloud” (DRC), observed with ALMA and superimposed on a *Spitzer* IRAC image, was found because of its extremely red *Herschel* SPIRE far-IR colors.

Discoveries like this have continued since the first discovery as more of the *Herschel* archive has been explored. For example, as recently as April 2018, two papers (Oteo et al., 2018) (Miller, 2018) with significant U.S. contributors and *Herschel*-related source selection have uncovered two different proto-clusters containing 10-14 galaxies squeezed into tiny cluster cores at z = 4. One of the proto-clusters, descriptively named the “Distant Red Cluster” (DRC), was found by virtue of its very red *Herschel* SPIRE colors.

The second—although first discovered with the South Pole Telescope—was later also found to share the same very red sub-mm *Herschel* colors as the DRC (Miller, 2018). The DRC proto-cluster at z = 4.3 has a measured total star formation rates, when summed over the whole proto-cluster cores, of 14,400 solar masses per year! This is the largest star formation rate for any structure so far observed in the Universe. The fact that these individual galaxies are found in such a small volume and already seem to live in massive halos of $>10^{13}$ solar masses suggests they are the progenitors of the most massive giant clusters in the local Universe. Even more impressive is the total gas mass associated with these objects, which reaches 10^{12} solar masses at z = 4, which correspond to only 1.6 billion years after the Big Bang. The discovery of such remarkable structures at high redshift bodes well for the discovery potential of future space observatories, such as *James Web Space Telescope* (JWST*)*, and telescope concepts like the *Origin Space Telescope* (OST), which would be capable of detecting emission from many atomic and molecular species at very high redshifts.

5. NHSC Role in the U.S. User Community

The NHSC provided the following important services to the *Herschel* user community that would not have been possible without the close involvement of NHSC science/technical staff and management in all aspects of the *Herschel* project. This was a result of strong and early close contact with members of the *Herschel* instrument teams (ICCs) and the ESA *Herschel* Science Center.

- **Organized a pre-launch science/community engagement** (2009) and Laboratory Astrophysics workshops (2006) in advance of the first proposal cycle deadline.
- **Organized eight data or archive processing workshops and mini-workshops** in Pasadena, CA, for targeted groups from 2009-2014. Many of these workshops had both local and “virtual”

attendance, with the ability to "desktop share" user problems. NHSC staff also provided some technical support for similar workshops in Europe.

- **Prepared special online tutorials for working with Herschel data.** These included specialist topics and data processing help for all three instruments, as well as specifically support tutorials for bridging heterodyne technology and methods for non-experts.
- **Provided expert technical help for proposing DDT or TOO-type rapid-response proposals** to those who requested them. Several time-critical proposals were initiated with significant help from NHSC staff.
- **Presented NHSC-organized webinars ("online tutorials")** on topics relating to general data processing, as well as more specific areas of interest association with individual NHSC instrument teams.
- **Provided a fully online helpdesk for U.S. users to gain rapid responses to questions.** The helpdesk became a prototype for the European HSC Helpdesk. NHSC and HSC staff had access to both helpdesks, allowing the flow of questions and information between the two centers.
- **Provided fully-resourced, on-site visitor help for visitors coming to IPAC to work on their data.** This included access to large memory virtual-machines (VM), and expert staff assistance with technical issues.
- **Provided "Project Wiki," WebDav and access to telecom (WebEx) facilities to encourage collaboration among U.S.-based observers.** In all, about 10 teams took up the offer of wiki page and WebDav facilities during the mission. One group used the facilities until 2018.
- **Provided "remote user" access by to large virtual machine (VM) computer resources (memory and CPU).** The machines were pre-loaded with Herschel software and large disk-space access was granted to users to prepare their observations for large computing jobs. This cloud-like solution pre-dated the cloud computing era, and was a very successful program involving 3-10 users at any one time using facilities through the mission.
- **Provided a full suite of science wiki pages to appraise U.S. users of important current events** and documentation. In tandem with a frequent newsletter and helpdesk, this was an important communication channels with users.

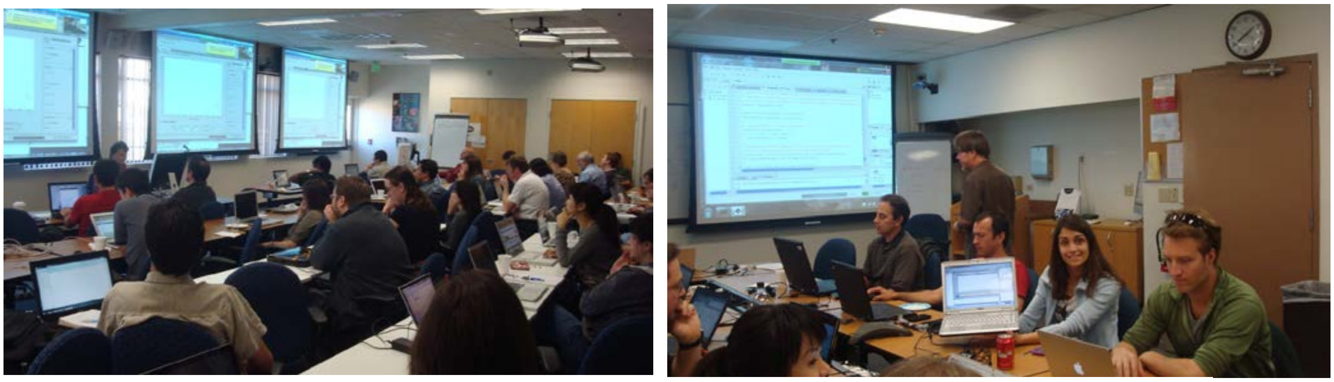


Figure 20: (Left) Example of a data processing workshop held in Pasadena in 2011. (Right) A hands-on data processing HIFI working session led by NHSC staff member Patrick Morris.

Figure 21: Group photo of a pre-launch data processing workshop held in Pasadena in April 2009, just one month before the launch of *Herschel*.

6. *Herschel* Advocacy

6.1 *Herschel* Science Advocacy within the U.S. Community

The NHSC helped organize and host many activities to familiarize the U.S. community with the *Herschel* mission. These included *Herschel*-related science conferences held in Pasadena, California under IPAC sponsorship. We also encouraged community engagement at large national meetings including Special Sessions and an NHSC booth at meetings of the American Astronomical Society and other major topical meetings. Electronic communication included a regular (at least monthly during the active mission) NHSC newsletter and a public outreach website describing *Herschel*-related science. The NHSC was extremely visible at winter and summer meetings of the American Astronomical Society, including several Hyperwall presentations in recent years.

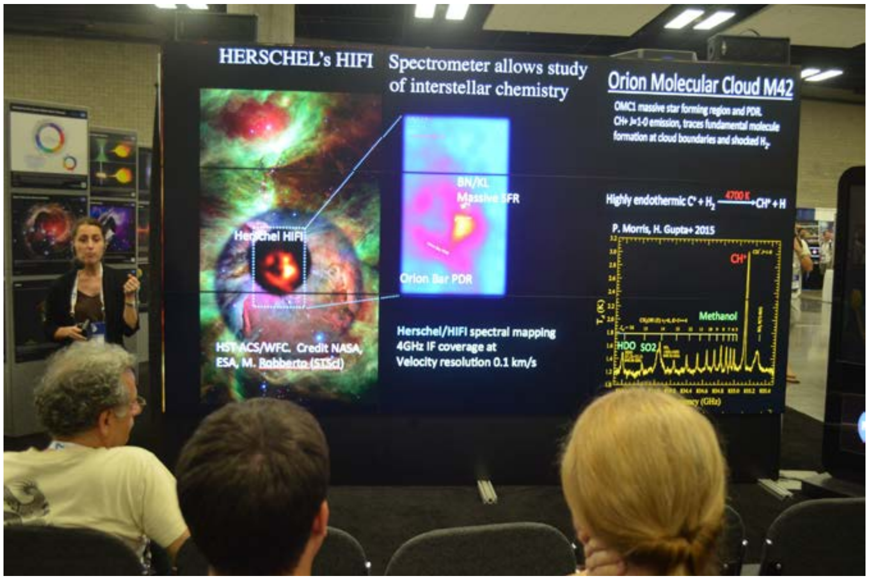
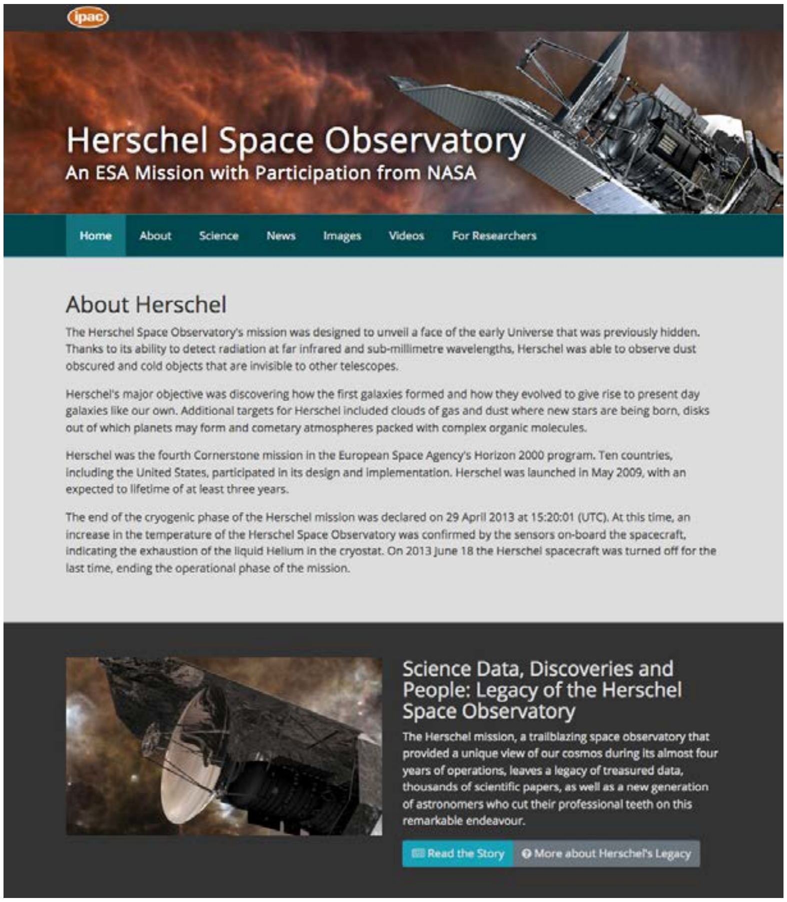


Figure 22: Part of the "Hyperwall" presentations given by NHSC staff scientist Dr. Roberta Paladini at the IAU General Assembly in 2015 in Hawaii on the importance of the Herschel Science Archive in Post-operations.

6.2 Public Advocacy

Engaging the general public in the excitement of *Herschel* is another area where the NHSC played a role. We supported a public outreach page, through IPAC Communications and Educations (ICE) team, which included many "image releases" and generating material for press releases from both NASA and ESA, especially when the U.S. community was leading the discoveries. We helped organize "*Herschel* Week" in September 2017, in which we coordinated releases of U.S. and ESA articles and videos on the web and social media to celebrate the science legacy for a more general audience. (See http://sci.esa.int/herschel/59492-herschel-week and https://www.herschel.caltech.edu.)



About Herschel

The Herschel Space Observatory's mission was designed to unveil a face of the early Universe that was previously hidden. Thanks to its ability to detect radiation at far infrared and sub-millimetre wavelengths, Herschel was able to observe dust obscured and cold objects that are invisible to other telescopes.

Herschel's major objective was discovering how the first galaxies formed and how they evolved to give rise to present day galaxies like our own. Additional targets for Herschel included clouds of gas and dust where new stars are being born, disks out of which planets may form and cometary atmospheres packed with complex organic molecules.

Herschel was the fourth Cornerstone mission in the European Space Agency's Horizon 2000 program. Ten countries, including the United States, participated in its design and implementation. Herschel was launched in May 2009, with an expected to lifetime of at least three years.

The end of the cryogenic phase of the Herschel mission was declared on 29 April 2013 at 15:20:01 (UTC). At this time, an increase in the temperature of the Herschel Space Observatory was confirmed by the sensors on-board the spacecraft, indicating the exhaustion of the liquid Helium in the cryostat. On 2013 June 18 the Herschel spacecraft was turned off for the last time, ending the operational phase of the mission.

Science Data, Discoveries and People: Legacy of the Herschel Space Observatory

The Herschel mission, a trailblazing space observatory that provided a unique view of our cosmos during its almost four years of operations, leaves a legacy of treasured data, thousands of scientific papers, as well as a new generation of astronomers who cut their professional teeth on this remarkable endeavour.

Figure 23: Screenshot of the NHSC Public Outreach page for *Herschel*.

6.3 Availability of Archival Science Data for U.S. Investigators

During and after the end of the active “on-orbit” mission, the NHSC engaged fully in the process of making the *Herschel* archival data easily available to U.S. users. This was done in several ways:

- **NHSC staff helped refine the data processing pipelines to provide the best possible archival products,** which stand as the legacy of the *Herschel* project. NHSC played a special role in helping compare different photometric mapping methods (leading to several published reports) across the PACS and SPIRE instruments, which resulted in improved photometric products. HIFI team members worked to generate “ready for science” spectral products delivered to the community through IPAC’s Infrared Science Archive (IRSA) and the *Herschel* Science Archive (HSA) in Europe. These “Highly Processed Data Products (HPDPs) were specially processed and did not assume that users had prior experience with heterodyne or photometric instruments.
- NHSC scientists helped develop **interfaces between *Herschel* Science Archive (HSA) in Europe and the IPAC Infrared Science Archive (IRSA)**. Initially allowing for simple metadata searches, the interfaces were later upgraded to include the ability of users to explore high-level products with sophisticated IRSA GUI interfaces, and search algorithms.

- **User-provided Data Products (UPDPs)**; high-level data products provided by the Key Programs and other large user projects) were often delivered to the *Herschel* project in a format which was not very user friendly—often involving large tar-balls of miscellaneous files and documentation placed on an ftp site. Recognizing the importance of these products, and to significantly improve the user friendly nature of these “Legacy-like” data deliveries, NHSC worked with IRSA to create very user-friendly interfaces with the data and documentation. By 2018, 15 Galactic and 11 extragalactic and one Solar System set of UPDPs have been successfully interfaced with IRSA (see https://irsa.ipac.caltech.edu/Missions/herschel.html).
- **SPIRE Point Source Catalog**: Towards the end of the *Herschel* mission, NHSC staff produced a “value-added” SPIRE photometry point source list for all SPIRE fields, include observations that were not part of the original SPIRE deep fields, but included serendipitous point source detection in small GO targeted fields not originally intended for point-source detection. The SPIRE photometer was known to hit the confusion limit for almost any targeted observation in a few seconds, and so the depth of these fields generally quite good in comparison with the special deep fields which are completely limited by source confusion. However, unlike the *Herschel* deep fields, most of these target fields did not have associated *Spitzer* imaging that could be used to provide priors for source extraction, and so the catalog was restricted to brighter sources, and, like all of the SPIRE catalogs, cannot separate sources that are close together on the sky compared to the beam size. A similar catalog was created in Europe for the PACS photometer, but this was mainly produced outside of NHSC.
- **Archival Science Workshops:** To develop awareness within the U.S. community of the immense riches of the *Herschel* archive and how best to exploit them, the NHSC hosted “archive-centric” workshops in which many new users, unfamiliar with the far-IR/sub-mm, were inspired to work with the *Herschel* data for their own projects. NHSC also conducted significant outreach efforts (through IPAC conferences and large national astronomical meeting) to advertise the science of *Herschel* (e.g., Hyperwall presentations, etc.).

7. Software Development within the *Herschel* Project

An important part of our ability to provide technical support to U.S. users through the many interfaces already described was the way we embedded, from an early time, our scientists and engineers in the *Herschel* project and software development. Here, we list some of the more important highlights of the *Herschel* project where NHSC played a particularly important role in initiating and developing specific activities that contributed to the *Herschel* project. The list is not meant to be all-inclusive, but provides examples of the activities initiated or primarily developed at NHSC that contributed to the success of the mission. Most of these tasks were performed in close association with our ESA counterparts.

7.1 Pre-launch Development

NHSC scientists and engineers worked with their respective ICCs, on pre-launch instrument level tests (ILTs), instrument and system testing with the integrated observatory (e. g., thermal balance/thermal vacuum tests), as well as data propagation from the MOC to the HSC and ICCs. NHSC staff also participated in testing at JPL of detectors and other focal plane components before integration into the HIFI and SPIRE instruments.

NHSC also conducted early research in support of the *Herschel* Common Software System, including evaluating existing Java graphics and numeric libraries (including taking over the Numerics library in HIPE in 2006) and other software tools (e.g., TablePlotter).

7.2 Development of *Herschel* Observation Planning Tools (HSpot) Interfaces

NHSC helped with early planning for observations and data processing software. In particular, the *Herschel* Observation Planning Tool (HSpot) was an adaptation of the *Spitzer* Observation Planning Tool (Spot) developed at IPAC for the *Spitzer* mission. IPAC helped with the top-level code export, core code debugging, and Astronomical Observation Template (AOT) development support.

NHSC provided the two computer servers that interfaced with the HSpot software via the Internet. These were the infrared background (Zodiacal light) estimator, derived from IPAC's experience with the Spitzer mission, and a background confusion estimator. These servers, supported and operated at IPAC, continued to support HSpot throughout all parts of the project.

7.3 Instrument-Specific Software Development

7.3.1 Software for PACS

- NHSC developed a **PACS photometer instrument simulator** in the pre-launch phase of the project.
- **Microwave Anisotropy Dataset Mapper (MADmap)** map-making algorithm for *Herschel*. Adapted from (and loosely based on) a software tool originally developed for cosmic microwave background data by a team at Lawrence Berkeley National Labs, MADmap was used in the early PACS Standard Product Generation (SPG) pipelines for photometric mapping. The module was eventually replaced by other methods.
- **Cube-building.** Initial development (in close association with the PACS ICC) of the cube-building infrastructure for the PACS spectrometer pipeline.
- **PACS Spectrometer Unchopped mode.** Transient Correction algorithms and scripts for correcting data from the "Unchopped Mode" of the PACS spectrometer.
- **Simplified Interface Making PACS Look Easy (SIMPLE).** An interactive tool for processing PACS photometer data. It does not require any knowledge of HIPE, and it works with a command line interface as well as in batch mode. It allows users to perform both data reduction and photometry on large PACS datasets, using the significant computing power at IPAC.

7.3.2 Software for SPIRE

- Development of the **Table/Over-plotter software in HIPE** used to allow users to explore SPIRE data.
- The development of a **graphical user interface for SPIRE data** called the SPIA (SPIRE Interactive Analysis) package. Initially a stand-alone package, it was eventually incorporated into HIPE. The package allowed users to easily run the SPIRE photometry pipeline and modify input parameters to explore the results.
- **SPIRE De-striper** was developed and integrated into HIPE. The de-striping algorithm became the primary mapper for the SPIRE photometer.

- **SPIRE Point-source Catalog.** NHSC led and developed the tools and methods to construct a point-source catalogue for SPIRE photometric observations.
- The SPIRE team, led by NHSC, a developed **cross-calibration effort with the *Planck* observatory**, establishing a zero-point correction for SPIRE photometric maps, in collaboration with the *Planck* consortium, HSC and SPIRE ICC.
- Final **full-beam profile analysis**.

7.3.3 Software for HIFI

- Spectral survey **sideband de-convolution tool**.
- Optical standing wave and **baseline artefact-correction algorithms** and interactive tools.
- **Noise characterization and performance algorithms.**
- **Mixer and Local Oscillator** spurious response detection, characterization, and trending.
- **Computing infrastructure for bulk processing and HIFI pipeline testing**, performance, and trending.
- Telescope pointing **performance and refinements**.

7.3.4 Software Acceptance and End-to-End Product Testing

- **Astronomer acceptance testing** of HIPE public releases and tools.
- **End-to-end testing** of *Herschel* Archive Products.

APPENDIX A: REFERENCES FOR RESEARCH HIGHLIGHTS

[1] Pilbratt, G. L., Riedinger, J. R., Passvogel, T., et al., 2010, A&A, 518, L1

[2] Poglitsch, A., Waelkens, C., Geis, N., et al., 2010, A&A, 518, L2

[3] Hartogh, P., Lis, D. C., Bockelée-Morvan, D., et al., 2011, Nature, 478, 218

[4] Griffin, M. J., Abergel, A., Abreu, A., et al., 2010, AAP, 518, L3

[5] de Graauw, T., Helmich, F. P., Phillips, T. G., et al., 2010, AAP, 518, L6

[6] Bergin, E. A., Cleeves, L. I., Gorti, U., et al., 2013, Nature, 493, 644

[7] Hogerheijde, M. R. et al., 2011, Science 334, 338–340

[8] André, P., Men'shchikov, A., Bontemps, S., et al. 2010, A&A, 518, L102

[9] Gerin, M., de Luca, M., Black, J., et al., 2010, A&A, 518, L110

[10] Neufeld, D. A., Goicoechea, J. R., Sonnentrucker, P., et al., 2010, A&A, 521, L10

[11] https://scitechdaily.com/astronomers-discover-ionized-molecules-in-markarian-231/

[12] González-Alfonso, E., Fischer, J., Bruderer, S., et al. 2018, ApJ, 857, 66

[13] Fischer, J., Sturm, E., González-Alfonso, E., et al. 2010, A&A, 518, L41

[14] Sturm, E., González-Alfonso, E., Veilleux, S., et al. 2011, ApJL, 733, L16

[15] Veilleux, S., Meléndez, M., Sturm, E., et al. 2013, ApJ, 776, 27

[16] Rangwala, N., Maloney, P. R., Glenn, J., et al. 2011, ApJ, 743, 94

[17] Dale, D. A., Aniano, G., Engelbracht, C. W., et al. 2012, ApJ, 745, 95

[18] Sandstrom, K. M., Leroy, A. K., Walter, F., et al. 2013, ApJ, 777, 5

[19] Kennicutt, R. C., Calzetti, D., Aniano, G., et al. 2011, PASP, 123, 1347

[20] Elbaz, D., Dickinson, M., Hwang, H. S., et al. 2011, A&A, 533, A119

[21] Lee, N., Sanders, D. B., Casey, C. M., et al. 2015, ApJ, 801, 80

[22] Riechers, D. A., Bradford, C. M., Clements, D. L., et al. 2013, Nature, 496, 329

[23] Fu, H., Cooray, A., Feruglio, C., et al. 2013, Nature, 498, 338

[24] Dowell, C. D., Conley, A., Glenn, J., et al. 2014, ApJ, 780, 75

[25] Oteo et al. 2018, ApJ, 856, 72

[26] Miller, T. B. et al., 2018, Nature, 556, 469

[27] Cavalié, T.; Feuchtgruber, H.; Lellouch, E. et al., 2013, A&A, 553, 16