Mem. S.A.It. Suppl. Vol. 19, 346
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Memorie della
Supplementi

The *Herschel* Space Observatory: Early results from the first year of activity

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Abstract. The *Herschel* Space Observatory is the largest infrared/submillimeter telescope launched to date. Equipped with instruments able to observe between 55 and 671 μm, *Herschel* is suited to probe the peak emission of the cold (few tens K) dust and to measure the brightest molecular and atomic emission lines of the cold/warm (from tens to hundreds K) gas. We overview the *Herschel* mission, describing the main scientific motivations behind the project and reporting the major results in its first year of activity.

Key words. space vehicles - space vehicles: instruments - infrared: general - submillimetre: general - stars: formation - ISM: structure

1. Introduction

The *Herschel* Space Observatory represents one of ESA cornerstone missions. It is the largest single-mirror telescope ever launched, observing at far infrared/submillimetric wavelengths, in the range from 55 to 671 μm (Pilbratt et al. 2010).
Launched on 14^{th} May 2009 together with the *Planck* satellite (see Mandolesi contribution in these proceedings), *Herschel* is currently in orbit around the second Lagrangian point (L2) of the Sun-Earth/Moon system, 1.5 milion km away from the Earth. The spacecraft is equipped with a 3.5 m diameter Cassegrain telescope passively cooled to a temperature of 80 K and a superfluid helium cryostat containing the scientific payload and the cooling liquid. The depletion time of liquid helium will determine the duration of the mission, which is currently estimated to be about 3.5 years.

2. The *Herschel* mission: An overview

2.1. Why an infrared space telescope ?

The *Herschel* mission follows the path traced by the previous infrared cryogenic space telescopes like IRAS (Neugebauer et al. 1984), ISO, *Spitzer* Space Observatory (Werner et al. 2004), and AKARI (Murakami et al. 2007), offering better sensitivity and spatial resolution thanks to a larger telescope diameter and higher sensitivity detectors. In addition, the instrument payload was designed to observe the far infrared/submillimiter wavelengths, see Fig. 1, filling the existing gap between the aforementioned space missions and the radio astronomy, both from space (SWAS, Melnick et al. 2000, and Odin, Nordh et al. 2003;

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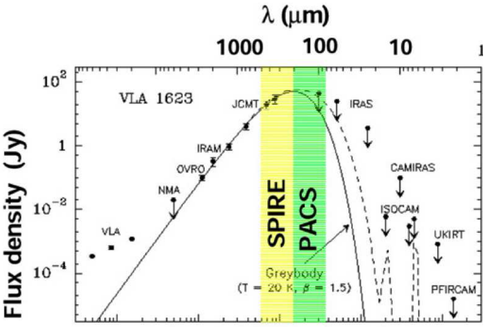

Fig. 1. Spectral coverage of *Herschel* instruments PACS and SPIRE compared to other space telescopes and ground facilities. Figure from Pilbratt et al. (2001).

Frisk et al. 2003) missions and from ground.

Herschel observations cover the emission peak of the cold dust (with temperature between 5 and 50 K) and include the brightest molecular and atomic emission lines of the cold/warm gas (with temperature between 10 and ~ few 100 K). Such gas and dust physical conditions are typically found in the diffuse interstellar medium (ISM) and in star forming molecular clouds. Hence, one of the main scientific goals of the mission is to study the physical and chemical processes active in the ISM and during the early stages of star formation, in our and nearby galaxies. To this aim, *Herschel* directly detects the pre- and protostellar cores deeply embedded into the molecular clouds, not observable otherwise at shorter wavelengths due to the high extinction caused by the surrounding dust. Studies on a statistically large sample of objects at different evolutionary stages will help answering the open questions concerning the earliest phases of star formation. At the same time, *Herschel* traces the diffuse ISM emission, determining its structures, physical properties, dynamics, and composition. Such information is crucial to characterize the complex ISM/star lifecycles.

Furthermore, cold dust is known to be present in discs surrounding many main sequence stars (Greaves et al. 2010). Those debris discs are the relics of the primordial accretion discs, depleted by the gas and the original dust, and are composed by dust resulting by distructive collisions between remnant planetesimals (e.g., asteroids and comets) orbiting in close proximity to one other. The occurrences and the properties of such structures constrain the current theories on the formation of planetary systems like our own.

On other side, the bulk of the radiation emitted by the star-forming galaxies far up to z ~5 also falls in the *Herschel* observable range. Thus, using *Herschel* data it is possible to characterize the formation of galaxies in the early universe and their subsequent evolution, analyzing the star formation activity through the cosmic time, and to investigate the AGN/starbust galaxies symbiosis.

Finally, *Herschel* will study solar system bodies, e.g. comets, asteroids and outer planets, in order to determine the chemical composition of their atmospheres/surfaces, complementing the direct exploration carried out with space probe missions.

2.2. Instrument payload

To achieve the scientific objectives mentioned above, the spacecraft is equipped with three instruments:

- PACS (Photodetector Array Camera and Spectrometer); Poglitsch et al. 2010: a dual-band photometer (first band fixed at λ_c = 160 μm while the second is chosen between λ_c = 70 or 110 μm) and a low to medium resolution integrated field line spectrometer (R ~1000-4000).
- SPIRE (Spectral and Photometric Imaging REceiver); Griffin et al. 2010: a three simultaneous band (λ_c = 250, 350, 500 μm) photometer and a low to medium resolution Fourier transform spectrograph (R ~1000-4000).
- HIFI (Heterodyne Instrument for the Far Infrared); de Graauw et al. 2010: a very high resolution heterodyne spectrometer (R ~10^6).

Table 1. Scientific payload mounted on *Herschel* Space Observatory (Pilbratt et al. 2010).

HIFI	Heterodyne spectrometer
Wavelength coverage	157-212 & 240-625 μm
Field-of-view	single pixel, 13-40 arcsec on sky
Spectral resolving power	$\sim 10^6$
PACS	2-band imaging photometer
Wavelength coverage	60-85 or 85-130, 130-210 μm
Field-of-view	0.5Fλ sampled $1.75' \times 3.5'$
PACS	Integral field spectrometer
Wavelength coverage	55-210 μm
Field-of-view	(5×5 pixel) $47'' \times 47''$
Spectral resolving power	1000-4000
SPIRE	3-band imaging photometer
Wavelength coverage	($\lambda/\Delta\lambda$ - 3) 250, 350, 500 μm
Field-of-view	2Fλ sampled $4' \times 8'$
SPIRE	Fourier transform spectrometer
Wavelength coverage	194-324 & 316-671 μm
Field-of-view	2Fλ sampled circular $2.6'$
Spectral resolving power	370-1300 (high) / 20-60 (low)

A summary of the instrument characteristics is reported in Tab. 1. For a further description of the instruments and their observing modes (OMs) refer to Calzoletti et al. included in these proceedings.

2.3. Mission plan

One month after the launch, *Herschel* entered in a stable orbit around the L2 and opened the cryo-cover, starting the Commissioning Phase (CoP) of the mission. For the following two months, the spacecraft functions and performances were checked, while the telescope and the instruments were cooled to the operational temperature. With the switching on of the instruments and the check of their functionality, the mission entered in the Performance Verification Phase (PVP), lasting three months, during which the performances and the calibrations for each instrument, the focal plane geometry and the pointing accuracy were verified. Such inflight verifications were used to test and optimize the various OMs. After that, during the Science Demostration Phase (SDP), the approved OMs were applied to perform selected observations in the framework of the accepted Key Programs (KPs) to demostrate the capabilities of the observatory.

The scientific results reported in these proceedings come from the data acquired during the SDP. Finally, seven months after reaching the L2 point, *Herschel* started the Routine Science Phase (RSP) with the execution of the planned scientific observations.

3. Observing with *Herschel*: Opportunities and key programs

ESA decided to structure the *Herschel* mission as an observatory whose Observing Time (ObT) is divided between Guaranteed Time (GT) and Open Time (OT). Around one third of the total available ObT (~ 20000 h) is allocated as GT, owned by the different consortia partecipating to the mission, the remaining is classified as OT accessible to the scientific comunity. ObT is allocated through a series of Announcement of Opportunities (AOs), on different deadlines for GT and OT proposals. A special AO (both for GT and OT) was called before the launch to allocate time for the KPs. KPs are projects exploiting the unique *Herschel* capabilities to answer important questions, often requiring a large amount

Table 2. Allocate time in Key Programs divided per scientific case.

Science Case	N	Allocated Time (h)
Solar System	2	666.4
Star Formation and ISM	20	4450.7
Stars	2	544.6
Galaxies and AGN	13	2914.0
Cosmology	5	2682.0
Total	42	11257.7

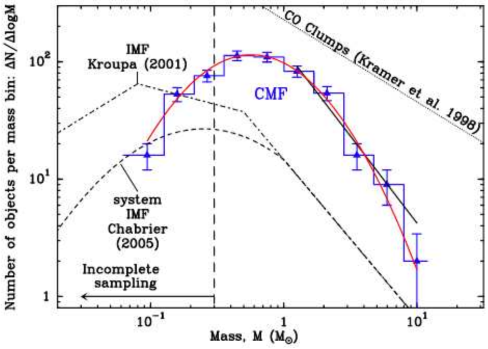

Fig. 2. Core Mass Function (blue histogram) derived from PACS and SPIRE observation of the Aquila Rift. The stellar Initial Mass Function (Kroupa 2001) is overplotted as well as the typical Clump Mass Function. Stellar IMF resembre the measured CMF with $M_\star \approx \epsilon_{core} M_{cores}$ with $\epsilon_{core} \sim 0.4$ in Aquila. Figure from André et al. (2010).

of ObT, that produce also wealthy datasets to be mined. They are mostly legacy programs, consisting in large spatial and spectral surveys, to be executed during the early phases of the mission in order to build up an all sky survey and to identify targets for follow up observations, possibly with *Herschel* itself.

The *Herschel* Observing Time Allocation Committee (HOTAC) selected 42 KPs (21 on GT and 21 on OT), divided among four different scientific areas (see Tab. 2), allocating 57% of the total OT. At least other two AOs are planned to occur during the RSP, separated approximately by one year from each other. In sight of such AOs, the Italian Space Agency (ASI) estabilished a section of the ASI Scientific Data Center (ASDC)[1] dedicated to support the Italian community with the planning of observational proposals, the data processing, the data quality control and the access to *Herschel* science archive.

4. First results from SDP data

One year after the launch, on May 2010, a large symposium was held in ESTEC[2] to show the first results obtained by the KPs from the SDP data. Those early results were published in a special issue of A&A[3], containing ~150 articles covering all the scientific cases listed in Tab. 2. It is not possible to summarize in this article all the results obtained from the first year of *Herschel* operations, we will instead concentrate on the main KPs where Italian institutions, like universities and INAF[4] research centers in Rome, Florence, Padua, Bologna, Lecce and Catania, played an active role. Such projects are mainly related to the large surveys on galactic and extragalactic scale.

4.1. Star Formation

Herschel is able to observe large portions of the sky simultaneously in five bands, adopting the OM with PACS and SPIRE in parallel mode (Calzoletti et al. 2010). Hence, it is particulary suitable to observe the extended star forming regions.

The Gould Belt Survey (on GT, PI: P. André and P. Saraceno; André et al. 2010) is a KP aiming to map the nearby star forming molecular clouds, belonging to the Gould Belt structure, between 70 and 500 μm. The aims are to produce a complete census of the protostars and the prestellar cores in the molecular cloud down to masses of ~ 0.01-0.1 $M_\odot$. The study of those objects allow to investigate the link between the prestellar core mass function (CMF) and the stellar initial mass func-

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[1] More information on http://www.asdc.asi.it/

[2] For a complete list of the topics see: http://herschel.esac.esa.int/FirstResultsSymposium.shtml

[3] A&A Special Issue Vol. 518 July-August 2010

[4] Istituto Nazionale di Astrofisica

tion (IMF) in very different enviroments, from active, cluster-forming complexes to the quiescent regions with a lower star formation activity. The analysis of the Aquila Rift and Polaris regions, observed during the SDP phase, revealed 2 to 9 times more objects than the previous studies , thanks to the *Herschel* higher sensitivity and spatial resolution. The preliminary results confirm that the CMF resembles the IMF scaled by a factor (efficiency factor, ϵ_{core}) of 0.2-0.4 (André et al. 2010), see also Fig. 2, indicating that the IMF originates from molecular cloud fragmentation as suggested by theory. The KP proposers also found that cores are not uniformely distributed in the star forming region, but they lies premintently along dense filamentary structures, formed by the turbulence acting within molecular clouds (Men'shichikov et al. 2010).

Such result is confirmed also in the early results of the Hi-GAL survey (Herschel Infrared study of the GALactic plane, on OT with PI: S. Molinari; Molinari et al. 2010a). Diffuse matter is found arranged in long filaments, along which the compact objects are typically found, (see Fig. 3) in both SDP maps, respectively centered at $(l,b) = (30^{\mathrm{o}},0^{\mathrm{o}})$ and $(59^{\mathrm{o}},0^{\mathrm{o}})$. The Hi-GAL KP is an unbiased PACS and SPIRE survey of the Galactic plane to map all the different phases of the ISM lifecycle: from the diffuse interstellar cirrus, to the dense molecular clouds, from the protostars to the post-AGB envelopes, from the supershells to the supernovae remants. With its richness, the Galactic plane represents the best laboratory to study the ISM/stars cyclic transformation, to understand how the molecular clouds, the massive (more than 8 $M_{\odot}$) stars, and the clusters form. Hence, the KP proposers plan to answer the major uncertainties on the theory of the star formation through the observations of a statistically high number of star-forming regions and cold ISM structures, in all the environments of the Milky Way, at all scales. Early results in this sense come from the study of the Infrared Dark Clouds (IRDCs), dark patches on top of the bright galactic plane background and thought to be the precursors of cluster forming sites, that appear in emission on Hi-GAL maps. Detailed studies revealed their structures, with a temperature drop (8-15 K) in their denser interior relative to the ambient (20-30 K) values (Peretto et al. 2010). The observations confirmed the existence of a column density threshold of $A_V \sim 5$, corresponding to $N_{\mathrm{H}} \sim 10^{21}$ cm^{-2}, for the core formation inside the filament under the action of the gravitational instabilities (Molinari et al. 2010b). The spectral energy distribution of large sample of cores and clumps has been modelled (Elia et al. 2010) with the existing models to understand how massive stars form. Finally, work is in progress to determine the importance of the massive stars for the triggering of further star formation (Zavagno et al. 2010). The relevance of their feedback on the enviroment has to be determined to better measure the star formation rate and efficiency in the Galaxy.

The HOBYS KP (Herschel imaging survey of the OB Young Stellar objects, on GT with PI: F. Motte; Motte et al. 2010) is more focused on how the high-mass stars form. It aims at mapping the regions that are actually forming OB-type stars, within 3 kpc from the Sun. OB stars are rare and fast evolving, nevertheless they are responsible for the ionization and the injection of energy in the ISM. Their stellar winds and supernova blast waves influence deeply the surrounding medium, sweeping and compressing the diffuse medium, triggering further star formation. Despite their importance, it is not clear how they form, mostly due to the low number of young OB objects observed in detail so far. HOBYS survey promises to increase the statistic. In their first observations, the KP proposers already found six high-mass protostellar cores ($M \geq 20$ $M_{\odot}$) in the Rosette molecular cloud. Those objects are compatible with a standard IMF (Kroupa 2001) and a lifetime of $\sim 10^5$ years (Hennemann et al. 2010). Moreover, quite few candidates of massive prestellar cores where identified in the same region. If all these cores are gravitationally bound, they represent the high-mass analog of the low-mass prestellar cores identified by Gould Belt survey. The KP proposers also found clear sign of the strong influence of the HII regions on the enviroment (Schneider et al. 2010; Anderson et al. 2010), determing the

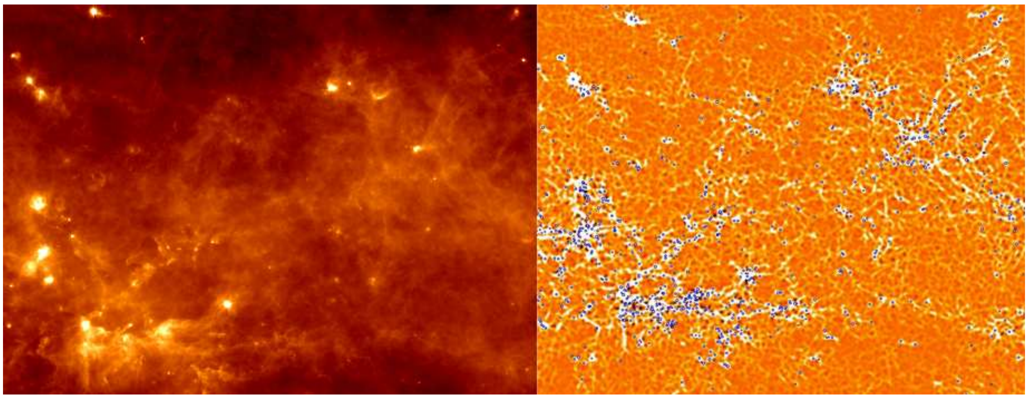

Fig. 3. Left panel: Hi-GAL map of a 2°x2° map centered at (l, b) = (30°,0°) observed with SPIRE at 250 μm. Right panel: filaments and sources distribution in such map. The filamentary structure is enanched by image processing techinques for curvature analysis (Molinari et al. 2010c). The blue dots represent the positions of the detected sources. Figure from Molinari et al. (2010b).

existence of a dust temperature gradient from 10 to 30 K along the ionized region of RCW 120.

In the framework of the star formation studies, there are some astrochemistry programs aiming to use HIFI instrument to produce molecular line surveys of the molecular clouds. Molecular lines offer a unique probe of the density, temperature, and kinematic properties within the cloud. Moreover, the chemical composition and evolution of the different molecules affect the mechanisms of star formation, since they are active coolants for the gas. HIFI is designed to have a wide spectral range and a high resolution to specifically study the cold and warm gas. It can observe the ground transition of many hydrides and the higher transitions of heavier molecules (like e.g. CO). Unfortunately, due to an electronic failure, HIFI was switched off early during the PVP, to be restarted later on January 2010. For such reason, spectral line KPs were delayed and their results were presented on a separate special issue of A&A, not yet available when this meeting was held. Nevertheless, early results from the data acquired before the shutting down look promising. The CHESS KP (Chemical Herschel Survey of Star forming regions, on GT with PI: C. Ceccarelli) is carrying out a spectral survey of the molecular content of star forming regions with different ages and masses (see for example Codella et al. (2010)). Complementary, WISH (Water in Star forming regions with Herschel, on GT with PI: E. Van Dishoeck) focus on PACS and HIFI observations of a sample of protostars to trace water lines (H_2O, $H_2^{18}O$, HDO) and the chemically related species (O, OH, OH^+, and H_3O^+). Water is the third most abundant species in the shocks, where the molecular oxygen converts into water, and in the regions warmed by recently formed stars. PACS observations, indeed, revealed high H_2O abundances (up to 10^{-4}) in the shocks formed in protostellar outflows. Those data shown that water is an important coolant, contributing for $\sim 27\%$ to the total energy released in the shocks (Nisini et al. 2010). Such an efficient cooling, of the order of $\sim 10^{-1}$ $L_\odot$, matches 40% of the one produced by the more abundant H_2 and it has to be taken into account in the energy budget for future modelling of shocks.

4.2. Galaxies

HeViCS (Herschel Virgo Cluster Survey, on OT with PI: G. Davies; Davies et al. 2010) aims at producing fully sampled maps of the nearby Virgo galaxy cluster with PACS and SPIRE. In their first observations, the KP proposers detected 400 galaxies, for which they determined the extension of the cold (T $\sim$20 K) dust emission in order to study its properties as function of the different galaxy type. They were able to measure the amount of the dust content in dwarf and giant elliptical galaxies, finding masses between 10^5 and 10^8 $M_\odot$ (DeLooze et al. 2010). Among the most interesting results, there are indications of considerable presence of dust in dwarf galaxies (up to $\sim 10^5$ $M_\odot$) with a metal-poor enviroment (gas to dust ratio of 10^{-3}; Grossi et al. (2010)). They also found that in the HI-deficient galaxies the dusty disc component is significantly reduced, matching the radius of the gaseous disc, due to truncation by the cluster enviroment (Cortese et al. 2010). Furthermore, they were not able to detect dust in the enviroment of early type galaxies, setting a limit of few tens Myrs to the dust lifetime in galactic enviroment (Clemens et al. 2010), before it is destroyed by the hot gas. Such a sort timescale implies that the intra-cluster enviroment could not be polluted by the stripping of the dust from early type of galaxies. Finally, a surprising result from *Herschel* data comes from the the far infrared luminosity function, appearing to be steeper than expected for faint galaxies, with a smaller number of objects detected than the previous surveys (Davies et al. 2010). Further data are needed to confirm such result.

4.3. Cosmology

A central problem in astrophysics is to understand how the galaxies form. To answer such topic, it is necessary to observe them in the far infrared/submillimeter, because the young galaxies are rich of dust that absorbs the optical/UV radiation and re-irradiates at longer wavelengths. A rough estimate indicates that half of the total cosmic energy density produced by galaxies comes from such radiation, showing the importance of those wavelengths for cosmological studies. Despite this, observations at such wavelengths were limited before the launch of *Herschel*. To cover such a gap, HOTACs approved two KPs, PEP (Pacs Evolutionary Probe on GT with PI: D. Lutz) and HerMES (Herschel Multi-tiered Extragalactic Survey on GT with PI: S. Oliver) to map with PACS and with SPIRE respectively, the evolution of infrared galaxies through the cosmic history. The two KPs are intimately linked and both have the goal to acquire deep field observations on sky-regions already sampled at shorter wavelengths. Between the primary science goal of those surveys there is the study of the Cosmic Infrared Background (CIB), composed by the emission of all the galaxies, at all cosmic epochs, at any wavelength (Dole et al. 2006). Thanks to *Herschel*, it is possible to resolve ~50% of the CIB at PACS bands and ~ 15% at 250 μm into individually detected sources (Berta et al. 2010; Oliver et al. 2010). Hence, for the first time, the CIB emission can be disentangled in the various components emitted at the different cosmic epochs (Berta et al. 2010). For every resolved galaxy up to $z \sim 3$, it was possible to determine the redshift, the luminosity, and mass refining the measures carried out with *Spitzer* data at 24 μm. Berta et al. (2010) found that the luminosities were overestimated by a median factor ~1.8 at $z \sim 2$, and underestimated up to a factor ~1.6 at $0.5 < z < 1.0$. Such data were used to determine the specific star formation rate, i.e. the ratio between the star formation rate and the mass, as function of the redshift, finding a slope $\alpha \sim$-0.25 for $z < 1$ and $\alpha \sim -0.5$ for $z \sim 2$ (Rodighiero et al. 2010). Anyway, when such a relationship is analyzed in a subsample of galaxies selected based on mass, it is found that the most massive ones ($M > 10^{11}$ $M_\odot$) have the lowest specific star formation rate, that is strongly increasing by a factor ~15 from local universe $z = 0$ to $z \sim 2$. This implies that those galaxies formed their stars earlier and faster than their low mass counterparts, a behaviour compatible with a downsizing scenario (Rodighiero et al. 2010). By disentangling each single galaxy contribution (Berta et al. 2010), the KP proposers were able to study the infrared luminosity functions at different z. They found that the infrared luminosity is dominated by a different galaxy population at different z, with spiral galaxies as the major emitters for $z < 0.2$, while the Seyfert 1 and 2 contribution is more relevant at higher redshift (Gruppioni et al. 2010). For $z > 1.5$ the starburst galaxies are the dominant emitters, again a clear sign that the main star formation activity shifted between different galaxy types with time. Vaccari et al. (2010), instead, compared the observed submillimetric luminosity function with the predictions from models of galaxy evolution. They found an excess of submillimeter population in the local universe with respect to the theoretical one. Such a discrepancy has to be addressed in order to constrain the formation and evolution of galaxies.

However, surveys were not only focusing on the high redshift sources. While PEP and HerMES will carry on deep observations on small fields, the H-ATLAS (Herschel Astrophysical Terahertz Large Area Survey on OT with PI: S. Eales; Eales et al. 2010) KP plan to observe with PACS and SPIRE a huge area of the sky ($\sim$ 550 square degrees) and produce a census of $\sim$250000 galaxies of the nearby universe. This will be the largest survey on the star formation so far (Clements et al. 2010): the previous IRAS survey was sensitive only to the hotter dust, while ground submillimeter observation have not covered enough area to sample a representative volume of the local universe.

5. Conclusions

From the local Solar system to the farthest galaxies, passing through the dense molecular clouds within Milk Way, the observations carried out with *Herschel* promise to improve our understanding of all fields related to star and galaxy formation and evolution. The *Herschel* Space Observatory is fully operative and is acquiring a wealth of data that will be mined for years. *Herschel* observations will open the path to a large number of follow-up studies, in view of the higher spatial resolution that future interferometric facilities, like ALMA, will offer. With its large scale surveys in far infrared/submillimetric, *Herschel* is th ideal precursor to ALMA, with both leaving a strong sign in the astronomy of 21^{th} century.

Acknowledgements. The authors wish to thank Michele Pestalozzi and Davide Elia for the given support. We also thank all the members of the various Key Programs who sent us material for the meeting. This work has been made possible thanks to the generous support of the Italian Space Agency via contract I/038/080/0.

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