The ALMA-Herschel Synergies

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One of the ESO-ESA science planning working groups has studied joint opportunities offered by Herschel and ALMA in the infrared and submillimetre bands. A brief summary of the report edited by David Elbaz and Tom Wilson is given here.

The ESA/Herschel Satellite and the Atacama Large Millimeter Array (ALMA) are two large projects in astronomy to investigate the submillimetre and Far InfraRed (FIR) range. Herschel covers the wavelength range from 60 to 625 μm (480–5000 GHz), while ALMA, an international project in which ESO has the European leadership, covers the range 320 μm to 1 cm (30–950 GHz). Both Herschel and ALMA will come into operation in similar timeframes. ALMA is planned to be completed in 2012, but 'early science' operation will begin well before this time. The launch of the Herschel satellite is planned for August 2007 with an expected lifetime longer than three years. Thus there should be an overlap in the time when both are in operation[1].

Although the two facilities overlap in wavelength range they are 'complementary'. They will lead to major advances in many fields of astronomy, especially those related to the origins of planets, stars and galaxies. The crucial questions are: (1) How do galaxies form? (2) How do stars form? and (3) What is the life cycle of a dust grain, and how does this depend on environment? The birth of planets, stars and galaxies is hidden by interstellar dust. The cocoons of forming objects are deeply embedded within gaseous dusty clouds where optical extinction can be extremely large and prevents the study of these fundamental processes with traditional optical telescopes. However, cool material emits submm and FIR radiation. By exploring this wavelength range we can directly measure physical phenomena associated with the formation process itself. The third question may seem less fundamental, but since FIR/submm telescopes measure radiation from dust, an accurate characterisation of dust properties is a prerequisite for answering the other two questions.

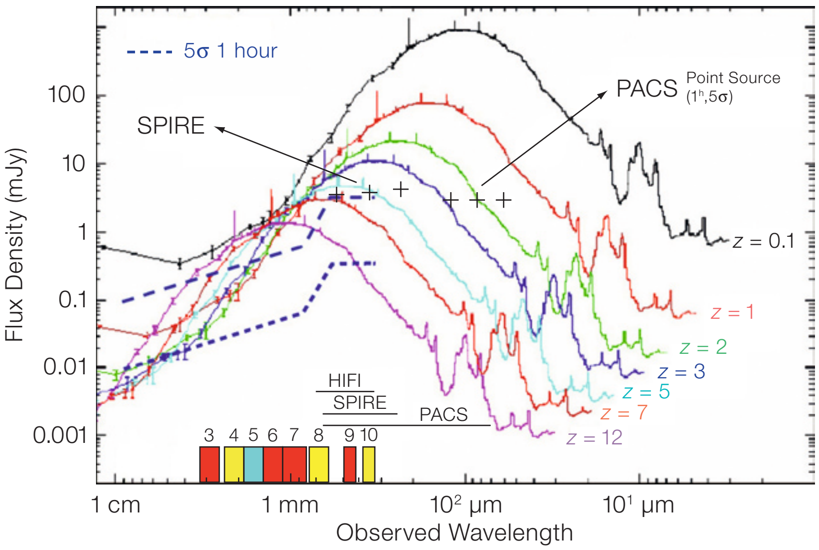


Figure 1: A plot of the emission from the starburst galaxy M82 for different redshifts, *z*. The horizontal axis is observed wavelength, the vertical axis is predicted flux density in mJy. The crosses show the sensitivity of the Herschel bolometers. The dashed lines at the left side of this diagram show the 5σ sensitivity of ALMA. The lower dashed curve is for the 64-antenna ALMA and the upper dashed curve for a 6-antenna ALMA. PACS, SPIRE and HIFI are Herschel receiver bands. The ALMA bands are shown numbered.

In the local Universe 30 % of the galaxies emit in the FIR/submm because they are dust enshrouded and forming stars. This fraction grows steeply up to redshift $z = 1–2$ and flattens off at earlier times, to $z > 6$, as inferred from the evolution of the cosmic luminosity density. This means that at redshifts larger than 1 the population of galaxies dominating cosmic energetics is that of dusty starburst galaxies, i.e. objects that are rapidly forming stars.

Figure 1 shows the Spectral Energy Distribution (SED) of the starburst galaxy M82, where the broadband radiation peaks in the FIR/submm. This is mostly due to thermal radiation from dust. This continuum radiation is consistent with temperatures in the range 10–100 K. In the FIR/submm/mm there are also spectral lines, mostly from molecular species, although there are prominent atomic fine structure lines of various ionisation stages of oxygen, carbon, silicon and nitrogen. Objects like M82 were much more frequent in the past. With the full ALMA we expect to detect 'M82-like' objects even at redshifts up to 12. As Figure 1 shows, if this SED is shifted in redshift, we witness a peculiar effect, called the 'negative K-correction', which greatly facilitates the detection of high-redshift objects at FIR/submm wavelength. The thermal spectrum and characteristics of dust emission makes the observed flux density constant at Herschel and ALMA wavelength range over a wide value of redshifts. This Figure shows that the broadband emission of sources such as M82 can be detected with Herschel and the early science ALMA even at high redshifts.

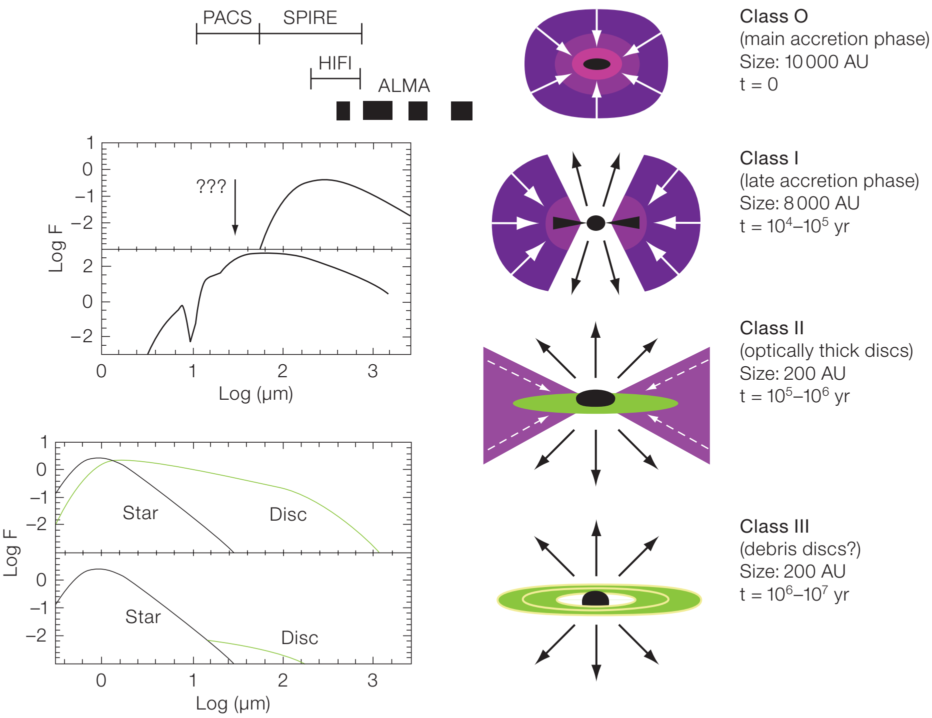
Our knowledge of the star-formation process is still very limited. Figure 2 shows a sketch of the four stages of star formation, from the collapse of a molecular

[1] A description of the bilateral (North America-Europe) ALMA is at *http://www.alma.nrao.edu/projectbk/construction/*. Accounts of ALMA science are in Shaver (1996) and Wootten (2001). The web site for the Herschel project, including all instruments, is *http://www.rssd.esa.int/Herschel/*. Accounts of Herschel and ALMA, some plans for Herschel science, ALMA science and their synergies are to be found in the Proceedings of "The Dusty and Molecular Universe" (ed. A. Wilson 2005).

cloud to the formation of a star surrounded by a disc. Cloud collapse requires high interstellar gas densities and low kinetic temperatures. The starting point is a gravitationally-bound 'pre-stellar core'. For column densities $N > 10^{18}$ cm^{-2} and densities $n > 10^2$ cm^{-3}, interstellar gas consists mostly of molecular hydrogen, H_2 and helium. This is a molecular cloud. The H_2 molecule does not produce emission lines if kinetic temperatures are below ~ 100 K and there are no shock waves. Then the abundances of the H_2 molecules must be traced indirectly. At high density, in cold clouds, grain properties change and constituents of the gas will condense onto grains. From millimetre-submm maps the mass distribution of pre-stellar cores is remarkably similar to the Initial Mass Function. These pre-stellar cores begin to collapse as the result of processes which may involve ambipolar diffusion, the dissipation of turbulence, or an outside impulse. Once begun, the gravitational collapse is rapid, ending in the formation of a hydrostatically-supported protostar in the centre. During the main accretion phase, the central object plus an accretion disc gradually builds up its mass from a surrounding envelope of matter while progressively warming. The protostar evolves from the Class 0 phase, in which the mass of the envelope is much greater than the mass of the protostar + disc, through the Class I stage, in which the mass of the protostar + disc becomes greater than the mass of the surrounding envelope, to the Class II stage, in which material in the envelope becomes sufficiently rarified that the protostar becomes visible to traditional optical telescopes. These phases can be distinguished by the shape of the FIR/submm SED.

With broadband data from Herschel/SPIRE and Herschel/PACS the SED shortward of the peak of the luminosity curve will be measured, with ALMA the longer wavelength part, so the total luminosity will be measured with accuracy. The Herschel spectrometers will measure the fine structure lines of atomic species and rotational and vibrational transitions of molecular species, without absorption in the Earth's atmosphere. This is especially important for water vapour lines, whose abundance has a strong influence on the energy balance and chemistry. The higher angular resolution of ALMA images will help to refine the analysis of models based on Herschel data. The final result will be the distribution of H_2, selected atoms, molecules and dust, as well as their dynamics.

Figure 2: A sketch of the development of a low-mass protostar and its disc (after Charles Lada, Figures: Michiel Hogerheijde). Above on the left side are shown the wavelength coverage of the Herschel instruments PACS, SPIRE and HIFI. The ALMA receiver bands from left to right are Band 9, Bands 7 and 6 and Band 3 in the bilateral ALMA project. With the addition of Band 5 and Bands 4, 8 and 10, the coverage of ALMA receiver bands provides a solid block in the uppermost part of the figure under 'ALMA'. These will also fill the longer wavelength part of Herschel HIFI coverage, marked 'HIFI'.



The Herschel PACS and SPIRE bolometer systems are well suited to surveying rather large regions of the sky, whereas ALMA can provide high sensitivity, high angular resolution images in spectral line and continuum, but these will usually be limited to a few arc minutes in size, at most. ALMA and Herschel/HIFI are heterodyne instruments, and will be able to resolve even the narrowest lines in velocity. Thus, ALMA is better suited to be a follow-up instrument for Herschel surveys. Such follow-ups could be in CO lines, to determine the redshifts of sources detected in the dust continuum, or in broad-band continuum to provide the component of spectral energy distributions at longer wavelengths. For spectral lines, ALMA will be complementary to Herschel because of different frequency ranges and attenuation in the Earth's atmosphere of most lines of water vapour. The higher angular resolution of ALMA provides high-resolution images of many spectral lines and allows better estimates of source sizes, the variations of abundances on scales finer than a few arc seconds and thus the true source averaged abundances of species which are those needed for chemistry models.

ALMA data alone and Herschel data alone will be a great step forward. A combined ALMA-Herschel data set will be a tremendous advance. A number of conditions must be fulfilled to combine Herschel and ALMA data sets. First, the calibrations for both instruments and cross calibration must be well determined and consistent. This will require a rather extensive set of Herschel measurements and subsequently, accurate models of the calibration sources. The signal-to-noise ratios must be excellent and the angular sizes of the calibrators well determined. This may restrict calibrators to Solar System objects. Herschel cannot observe sources closer to the Sun than Earth, because of Sun avoidance. Also the detectors will saturate when observing intense sources, so the calibrations may have to be done using the emission from asteroids such as Vesta, Ceres, moons of outer planets, or smaller planets such as Uranus, Neptune or Pluto. PACS and SPIRE cross calibration with ALMA will be more complex because the bandwidths of these instruments are much larger than those possible with ALMA.

For any spectral line surveys with Herschel, follow-up measurements with ALMA will greatly increase the scientific value. However, it must be stressed that this requires Herschel surveys to be as complete as possible.

For an efficient synergy, ESA should devote Herschel time to Legacy projects, i.e. projects of large interest for the community, starting soon after the science verification phase and/or during the very early Herschel lifetime. It should make data available to the community as soon as possible, and provide access to data-reduction tools and calibration. This would be the case for Herschel surveys of Galactic and extragalactic sources, in continuum and spectroscopy.

Most efficient would be a scheme in which ESO reacts quickly to Herschel data. It would be useful to allocate ALMA observing time as soon as possible to measure variable sources, newly discovered sources, peculiar objects or in general to perform a complete follow-up both in line and continuum of selected fields.

The data sets that will be produced by Herschel and ALMA will be so large that there may have to be special data-reduction procedures to insure the optimal synergy. The analysis and comparisons with models will have to be made on an automatic basis without human intervention. Such computer analysis programs have been developed by Schöier et al. (2005), for example, but these must be further developed to accommodate the very large data sets that will be produced by ALMA and Herschel in the near future.

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References

Schöier F. et al. 2005, A&A 432, 369
Shaver P. 1996, Science with Large Millimeter Arrays, Springer Verlag.
Wilson A. 2005, The Dusty and Molecular Universe ESA-SP577, ESTEC, Noordwijk, the Netherlands
Wootten A. 2001, Science with the Atacama Large Millimeter Array (ALMA), ASP Conference Series, Vol. CS 235

ESO at AAAS

Claus Madsen (ESO)

Even casual observers of ESO will have noticed a steady increase in public visibility for our organisation and its projects over the recent years. This increase is the result of a many-sided but focussed effort in public communication about ESO. Entertaining information stands at key fairs and conferences are part of this effort, and ESO's presence at this year's Annual Meeting of the American Association for the Advancement of Science – though a 'first' for us – is therefore no coincidence. This meeting is arguably the largest gathering of its kind worldwide. Indeed, no other event manages to attract more science journalists including a substantial number from Europe, which is certainly one of the reasons why more European organisations have begun to think about participating. Another reason is that the annual AAAS meetings provide plenty of opportunities for exchanges between American and European scientists and science policy makers.

This year's meeting took place on 16–20 February at America's Center in St Louis, Missouri. With an estimated 4 000 participants this meeting was one of the 'smaller' AAAS gatherings, but nonetheless it featured nearly 200 symposia, plenary and topical lectures, in-depth seminars, poster presentations, career workshops, etc. in addition to a major exhibition. ESO's 30 sq m information stand was located in the main exhibition hall, located near the stands of the National Science Foundation and the European Commission.

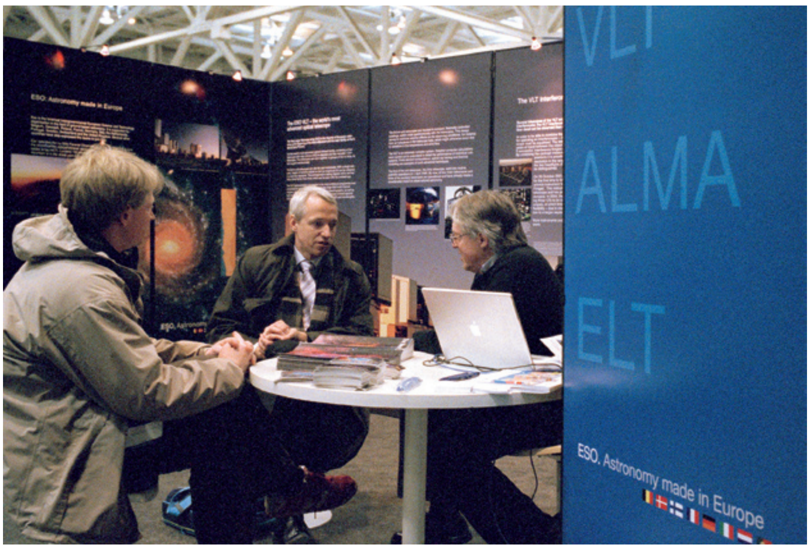

Photo: E. Janssen, ESO

Dr. Herbert Münder (middle), one of the organisers of Euroscience Open Forum 2006, at the ESO stand.