The origin of dust in galaxies in the Herschel and ALMA era

MEETING REPORT Haley Gomez and Mikako Matsuura summarize some of the recent Planck and Herschel data presented at an RAS meeting earlier this year.

The European Space Agency’s Herschel Space Observatory, launched in 2009, continues to unveil dusty galaxies and star-forming regions, revealing the unseen universe behind the dust “smoke screen”. Meanwhile, ESA’s Planck satellite has mapped the sky nearly five times and released early science papers while full analysis of the whole-sky survey is under way. This review covers some of the most important early results.

Dust grains are ubiquitous in the interstellar medium of galaxies. They are responsible for the formation of molecular hydrogen and for absorbing and re-emitting up to 90% of the energy from galaxies, as well as providing an effective coolant for star formation. Although important in various astrophysical processes, the origin and consequently the chemical makeup and emission properties of dust grains is largely unknown. Since the launch of ESA’s Herschel and Planck satellites in 2009, we are beginning to understand far more about the origin, evolution and composition of dust, required in order to correctly interpret results from studies of galaxy evolution and star formation in the far-infrared and submillimetre wavelength bands. This is especially important given the new facilities coming online, including the Atacama Large Millimeter Array (ALMA), the Space Infra-red telescope for Cosmology and Astrophysics (SPICA) and the Far-Infrared Interferometer (FIRI).

Herschel (Pilbratt et al. 2010) is an ESA-led mission that was launched in 2009 with routine operations beginning in January 2010. Herschel has two photometric and spectroscopic instruments covering 35–210 μm (PACS; Poglitsch et al. 2010) and 190–670 μm (SPIRE; Griffin et al. 2010) and a high-resolution heterodyne receiver covering 157–625 μm (HIFI; de Graauw et al. 2010). The full wavelength coverage allows us to fully sample the far-infrared and submillimetre regime for the first time, with exquisite resolution. As well as piecing together the relative contribution of stellar sources to the dust budget in galaxies, unravelling the key to massive star formation and detecting water in different environments, Herschel has put us in a position to measure the dust mass in hundreds of thousands of galaxies. An example of the dramatic change afforded by Herschel is shown in figure 1. This image shows a three-colour composite with Herschel SPIRE of a small patch of sky (covering 14 by 1.5 square degrees). This image is only a tiny fraction of the Herschel-ATLAS project (led by Loretta Dunne and Steve Eales); this study, combined with the HerMES HeLMS project (led by Marco Viero), will provide a legacy equivalent to the Sloan Digital Sky Survey for the submillimetre universe.

At the same time, Planck (Tauber et al. 2010) was launched with the aim of measuring the anisotropy of the cosmic microwave background (CMB) in sharper detail than ever before. Planck observes the sky at frequencies of 30–857 GHz with its two instruments: the High Frequency Instrument (HFI; Planck HFI Core team 2011) and the Low Frequency Instrument (LFI; Mandolesi et al. 2010). Although HFI has now exhausted its coolant, LFI is still taking data at the longer wavelength range with unprecedented sensitivity. Planck’s frequency coverage, combined with its sensitivity and high angular resolution, make it a powerful tool not only for cosmological studies, but also for investigating dust in nearby galaxies and the Milky Way.

The first session, chaired by Alexander Tielens (Leiden University), focused on reviewing the origin of dust in galaxies and understanding the physical properties and evolution of dust grains in the interstellar medium.

Alexander Tielens (Leiden University) gave the first invited review of the day on the lifecycle of dust in galaxies, astrochemical processes and the importance of molecules in providing unique information on the physical conditions in the universe. Alexander started off by discussing the dust inventory, which is highly uncertain (Tielens 2005). Dust is generally believed to form in the atmospheres of low/intermediate-mass stars on the asymptotic giant branch (AGB), but there is growing evidence that dust may also be formed in the explosions of massive stars. Figure 2 shows a summary of the relative contribution of stellar sources to the dust budget, with relative contribution indicated by size in the schematic and grey and blue colours indicating “uncertain” and “highly uncertain” sources respectively. With Herschel (together with previous work with the Spitzer Space Telescope), we are at last starting to probe the dust sources in the Milky Way and the Magellanic Clouds (see Anja Andersen’s and Mikako Matsuura’s contributions below) but pinning down the dust sources is still rather difficult.

Destruction of dust is clearly an important

1: A small fraction of the Herschel ATLAS survey (Eales et al. 2010) as imaged by SPIRE (combined three-colour image with blue 250, green 350 and red 500 μm) with the Moon shown to scale. In this region alone there are literally thousands of submillimetre galaxies. (The data is publicly available at http://www.h-atlas.org)
process in its lifecycle. Supernova shocks destroy grains by shattering and sputtering and this is thought to be rapid and efficient (e.g. Jones et al. 1994) with Stardust destroyed on a timescale of 500 million years or so in the Milky Way. Comparing this with the average dust injection timescale from low/intermediate-mass stars (roughly 2000 million years), there is clearly a significant dust accountancy problem: in galaxies, dust appears to be destroyed faster than it can be made. Dust formation in supernovae can alleviate this issue, though it is not clear how much dust is formed in the initial few years after a supernova explosion and how much is subsequently destroyed by the blast wave thousands of years after. This issue remains unresolved.

So what do astronomers agree on with regards to the properties of cosmic dust? Grain composition is reasonably well understood, with dust composed mainly of silicates and carbonaceous material, with sub-micron sized grains dominating the dust mass. We know also that some observed infrared features are due to emission from very small grains known as interstellar polycyclic aromatic hydrocarbons (PAHs), which provide an extension of the grain size distribution from micron-scale into the molecular domain; PAHs are also ubiquitous in the universe. Furthermore, there is evidence for icy mantles on the surface of grains. They are accreted in dense molecular clouds (evidence for this includes the different depletion levels of elements in dense clouds compared to the inter-cloud regions in the Milky Way), where mantle growth also helps get around the tricky dust-budget problem mentioned above. In this scenario, the mantle layer on the surface of grains is sputtered by shocks, leaving the grain “core” relatively intact.

Our understanding of the grain size distribution and basic composition – from depletion levels of elements in the interstellar medium, extinction curves and infrared spectral features – allows us to create detailed theoretical models of dust grains (e.g. Draine and Li 2007, Zubko et al. 2004). However, the models used are widely debated and although these models are very precise, they could also be highly inaccurate. Photometric and spectroscopic observations with space telescopes such as Herschel and Planck should constrain these models soon.

Alexander gave a final cautionary note to the audience that one should not be surprised if dust properties vary from one phase to another in different galaxies, since the observed properties should reflect the formation and processing of grains locally. He pointed out that dust properties could well be different (or indeed similar) in galaxies at different redshifts.

In his final comments, Alexander tackled the big unanswered questions in this field, including, “What is the origin of dust and the key physical processes in its evolution?” and “What are the true probes of dust at high redshifts?” Herschel and Planck have helped shed light on the origin of dust, including highlighting new physical properties (see Clive Dickinson’s and Matthew Smith’s contributions below), but there are still a lot of outstanding issues. With current facilities on hand such as ALMA and NASA’s Stratospheric Observatory For Infrared Astronomy (SOFIA), and with the James Webb Space Telescope (JWST) and SPICA on the horizon, the future certainly looks bright.

Making, baking and breaking dust

Anja Andersen (University of Copenhagen) gave the second invited review of the day with her talk “Making, baking and breaking dust in the ISM”. The large amounts of dust seen in galaxies and quasars at high redshifts is posing a problem for the traditional view that dust is formed in the atmosphere of low/intermediate-mass stars at the end of their lives. Anja showed that carbon grains formed in stars with C/O > 1 can easily drive the wind outward, but for atmospheres with C/O < 1 the silicate grains one would expect to form can only help drive the wind out (Höfner 2011). Given that we still observe these winds around C/O < 1 stars, this may suggest that carbon grains need to form even in oxygen-rich atmospheres.

Anja concluded by reiterating that dust sources in the early universe are really not well constrained, but one possible scenario is that AGB stars contribute only a minor fraction of the dust mass in galaxies at any time. Anja then echoed Alexander’s comment that stardust may only provide the seeds with grains “growing” further in dense regions of the ISM. She pointed out that in these dense regions we already know that hydrogen is converted into its molecular form. From a chemical point of view, the densities are also high enough to convert carbon, magnesium, silicate etc from the gas phase to solid phase. An interesting possibility is then whether this scenario is the dominant method of dust grain formation in galaxies, with dust formed in the atmospheres of stars playing only a minor part.

Iain McDonald (University of Manchester) expanded further on dust formation in AGB
stars, focusing on how metallicities can impact on grain formation in these atmospheres. Using Spitzer observations, he presented results from a study of spectra of these stars in galactic clusters and in nearby dwarf galaxies at a wide range of metallicities (McDonald et al. 2011). Recent studies have shown that crystalline silicates are mainly found in oxygen-rich stars down to a quarter of solar metallicity, but below this metallicity, crystalline silicate has not been detected, so far. Iain proposed that, instead, metallic iron is the major constituent of dust in giant stars at low metallicities (McDonald et al. 2010). Referring back to Anja Andersen’s talk on how dense winds in AGB stars are pushed outwards, Iain suggested that radiation pressure on these metallic iron grains can trigger outflows of gas in these stars. He finished by showing the audience why future ALMA observations are needed. First, ALMA will probe a different discovery space to previous telescopes (figure 4) pushing down to lower metallicities than observed before. Secondly, as well as providing the velocities of the outflows in clusters via line-emission diagnostics (hence determining the efficiency of this process), ALMA data will provide information on stellar mass-loss rates at a range of metallicities.

Returning to the topic of dust origins, Mikako Matsuura (University College London) stressed that our understanding of where dust forms remains incomplete. Her previous studies with Spitzer suggested that in the Large and Small Magellanic Clouds there is not enough dust being produced by low/intermediate-mass stars towards the end of their lives (Matsuura et al. 2009). Another source of dust is needed, and supernovae could be that source. The question is, how much dust do supernovae produce and how much do they destroy? Summarizing Herschel observations of supernova remnants from the Mass Loss from Evolved Stars (MESS, led by Martin Groenewegen; Groenewegen et al. 2011) and the HERschel Inventory of The Agents of Galaxy Evolution (HERITAGE, led by Margaret Meixner; Meixner et al. 2010) surveys, Mikako showed that Herschel has contributed significantly to our understanding of dust formation in supernova ejecta.

From these surveys, we now know that there is very little dust in the remnants of Type Ia explosions (e.g. figure 5 in Gomez et al. 2012a) but that core-collapse supernovae could be important contributors to the interstellar dust budget (e.g. Barlow et al. 2010, Gomez et al. 2012b). Somewhat surprisingly, Herschel recently detected emission from cold dust in SN1987A (figure 5), uncovering 230 000 Earth masses of dust in the ejecta (Matsuura et al. 2011). This dust appears to have been freshly formed only decades after the initial explosion, though it is unclear whether (over a long period of time) these grains will survive to contribute to the overall dust mass in the surrounding interstellar medium. One unresolved question is why dust appears to form efficiently in the ejecta of core-collapse supernovae but not in Type Ia remnants.

ALMA observations are now in hand for SN1987A, crucial to resolve unambiguously the spatial location of the dust (unresolved by Herschel), providing a definitive answer on whether this dust is in the ejecta and how important supernovae are to the dust budget in galaxies. ALMA, JWST and SPICA will no doubt shed light on these issues in the future.

**Nano-sized spinning dust grains**

To finish off the morning session, Clive Dickinson (University of Manchester) presented Planck results on the properties of dust grains in our galaxy. The talk began with a description of anomalous microwave emission (AME), a historical term given to the reported excess of microwave emission (10–100 GHz) observed in molecular regions in our galaxy which cannot be explained by synchrotron, free-free or thermal dust emission. This AME was known to correlate with the 100 μm emission from dust (as observed by the Infrared Astronomical Satellite [IRAS] in the 1990s; e.g. Leitch et al. 1997) but lacked data, and not enough coverage in the spectral energy distribution (SED), meant the origin or abundance of AME was unknown.

With unique frequency coverage of 28–857 GHz, Planck provides additional flux information that allows accurate comparison of models for AME for the first time. In one of the early results papers from the Planck team (Planck Collaboration et al. 2011), they investigated the spectral energy distribution of two known AME regions. These results provide the strongest support so far that AME originates from electro-dipole radiation due to small spinning dust grains. Not only does Planck confirm that the AME is well fit by a spinning dust
model, surprisingly they find that dust is ubiquitous in our galaxy. These results shine new light on an important constituent of the ISM, and as well as being a foreground for studies of the CMB radiation, this ultimately provides a new diagnostic for the properties of dust in galaxies. Clive summarized by saying that the theory of spinning dust is not fully constrained right now (data at even higher radio frequencies are needed), and it is possible the AME could originate from even stranger dust, so-called “magnetic grains” (e.g. Draine and Lazarian 1999). Polarization measurements may provide the capability to distinguish between these “weird dust” models.

**Dusty galaxies: near and far**

The afternoon session, chaired by Rob Kenicutt (Cambridge University) moved on to discussing the importance of dust and gas in galaxies at low and high redshifts, and the insights Herschel in particular has made in this area.

Chris Carilli (National Radio Astronomy Observatory) started this session off with the third invited review of the day covering what we know about dust, gas and star formation in the earliest galaxies. Infrared observations of these early galaxies are useful probes of galaxy evolution and star formation rates, and provide a constraint on the timescale of dust formation and destruction because of the short timescales available at redshifts greater than five. However, large-area surveys with Herschel are proving to be a problem since it is difficult to get redshifts of all the dust sources detected in these fields. The silver lining is that infrared data can be combined with radio observations, which, as well as giving redshift information, are a diagnostic of the atomic and molecular gas in these systems, providing a direct probe of the fuel available for star formation. Although ALMA will be extremely important in this area in the future (figure 6; Carilli et al. 2011a), currently the Jansky Very Large Array (JVLA) and Expanded VLA (EVLA) are already making strides at probing the ISM in both normal star-forming galaxies at intermediate redshift and submillimetre galaxies at higher redshifts (Carilli et al. 2011b).

The increased bandwidth of ALMA and EVLA means that, in every hour of observation with EVLA, we would expect to find many more early galaxies and measure their redshifts! Chris summarized by saying that ALMA and the EVLA will represent an order of magnitude, or more, improvement in terms of observational capabilities from 1 GHz to 1 THz, allowing astronomers to study astrophysical chemistry in galaxies at redshifts greater than six. These powerful advances will also make cosmological deep-fields viable for the first time, providing gas diagnostics of thousands of galaxies at redshifts 0.2–6.7.

Maud Galametz (University of Cambridge) brought us back to the local universe and presented results from the Herschel project KINGFISH (Key Insights on Nearby Galaxies: a Far-Infrared Survey with Herschel, led by Rob Kennicutt; Kennicutt et al. 2011). This sample of 61 galaxies covers a wide range of morphological classifications (figure 7) with the aim of investigating the properties of dust in resolved nearby galaxies. Among the many results from KINGFISH, Maud discussed the influence of the dust emissivity spectral index ($\beta$) on the total dust mass estimates as well as the well-known (but not well understood) correlation seen between $\beta$ and the dust temperature. One current hot topic is whether a significant mass of cold dust is present in some galaxies, raised by recent evidence of submillimetre excesses seen in low-metallicity systems from ground-based observations (Galametz et al. 2011) and in some Herschel SPIRE observations. Combining a small sample from the Herschel KINGFISH data with longer-wavelength imaging using the LABOCA camera (at 870 $\mu$m), Maud showed that the submillimetre excess also appears to be detected in large spiral galaxies, though this could be explained by the use of different dust models or different $\beta$ values. Maud finally discussed how using resolved studies of galaxies produces a higher dust mass estimate than unresolved global studies (Galametz et al. 2012). This highlights the need for resolved studies of galaxies with ALMA to obtain accurate dust masses.

On a similar note, Matthew Smith (Cardiff University) presented new results from the Herschel Reference Survey of 323 galaxies in the local universe (HRS, led by Steve Eales and Alessandro Boselli; Boselli et al. 2010). Herschel detected dust emission in roughly half of the sample of 62 early types and ellipticals, suggesting the latter galaxies are not all “red and dead” as often described. Interestingly, Matthew showed that Herschel is the most sensitive way to detect the interstellar medium in these galaxies, suggesting we may be able to use dust as a tracer of gas instead of the traditional carbon monoxide and atomic hydrogen lines.

The results from Herschel (see also Rowlands et al. 2012) indicate that traditional so-called “quiescent” galaxies can still have significant dust emission, star formation and interstellar material. However, comparing the dust masses of the early types with spiral galaxies from the HRS, they find an order of magnitude decline in the dust-per-unit stellar mass as they move across the Hubble sequence of galaxies from spirals, to S0s to ellipticals (Smith et al. 2012a). The high dust masses, the similar gas-to-dust ratios to spirals and the lack of correlation between starlight and dust, all point towards an external origin for the dust in ellipticals, i.e. the interstellar medium is accreted via tidal accretion or interaction with a nearby galaxy. Future observations with ALMA will be crucial in order to spatially resolve the Herschel ellipticals and address this issue.

The meeting finished with Steve Eales (Cardiff University) presenting Herschel results of our nearest spiral galaxy, M31, using data from the Herschel Exploitation of Local Galaxy Andromeda (HELGA, led by Jacopo Fritz; Fritz et al. 2012). The SPIRE image of M31 is shown in figure 8 (left), and with the excellent resolution afforded by Herschel and the wavelength coverage from 70–500 $\mu$m, it is possible to create a map of the dust surface density in each pixel, and to investigate the variation in the dust temperature, mass and $\beta$ with radius. In Smith et al. (2012, figure 8 right), they did exactly this, fitting modified blackbodies to the dust emission for approximately 4000 independent pixels, with a spatial resolution of a typical giant molecular cloud complex (roughly 140 pc). For the first time, this team was able to study dust emission in an external galaxy with enough resolution to pick out star-forming regions! This study highlights the tremendous advance in the quality of data in the far-infrared regime, particularly the major advances in being able to carry out resolved studies of dust in external galaxies. One of the many interesting results
from this study was the large variation in the dust emissivity index as one moves outwards from the centre of the galaxy towards the edge, possibly hinting at a real change in the physical properties of the dust grains. This brings us back to Alexander Tielen’s comments on how much dust properties change with environment.

The take-home message from the meeting was that Herschel and Planck are revolutionizing our understanding of the origin, evolution and properties of dust in the Milky Way and external galaxies. The meeting ended with a look to current and future facilities such as EVLA, ALMA, JWST, FIRI and SPICA, which will provide sharper images, increased sensitivity and improved spectral line coverage (figure 6) and combined with the legacy of Herschel and Planck, will allow us to pin down at last the outstanding issues described here.

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References
Boselli A et al. 2010 PASP 122 261.
Eales S A et al. 2010 PASP 122 499.
Rowlands K et al. 2012 MNRAS 419 2545.