Volume Title
*ASP Conference Series, Vol. **Volume Number***
Author

Results from the Herschel Key Program MESS*

M.A.T. Groenewegen[1], C. Waelkens[2], M.J. Barlow[3], F. Kerschbaum[4], P. Garcia-Lario[5], J. Cernicharo[6], J.A.D.L. Blommaert[2], J. Bouwman[7], M. Cohen[8], N. Cox[2], L. Decin[2], 9, K. Exter[2], W.K. Gear[10], H.L. Gomez[10], P.C. Hargrave[10], Th. Henning[7], D. Hutsemékers[15], R.J. Ivison[11], A. Jorissen[16], O. Krause[7], D. Ladjal[2], S.J. Leeks[12], T.L. Lim[12], M. Matsuura[3,18], Y. Nazé[15], G. Olofsson[13], R. Ottensamer[4,19], E. Polehampton[12,17], T. Posch[4], G. Rauw[15], P. Royer[2], B. Sibthorpe[7], B.M. Swinyard[12], T. Ueta[14], C. Vamvatira-Nakou[15], B. Vandenbussche[2], G.C. Van de Steene[1], S. Van Eck[16], P.A.M. van Hoof[1], H. Van Winckel[2], E. Verdugo[5], and R. Wesson[3]

[1]*Koninklijke Sterrenwacht van België, Ringlaan 3, B–1180 Brussel, Belgium*

[2]*Institute of Astronomy, University of Leuven, Celestijnenlaan 200D, B–3001 Leuven, Belgium*

[3]*Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT*

[4]*University Vienna, Department of Astronomy, Türkenschanzstrasse 17, A–1180 Wien, Austria*

[4]*Herschel Science Centre, European Space Astronomy Centre, Villafranca del Castillo. Apartado de Correos 78, E–28080 Madrid, Spain*

[6]*Astrophysics Dept, CAB (INTA-CSIC), Crta Ajalvir km4, 28805 Torrejon de Ardoz, Madrid, Spain*

[7]*Max-Planck-Institut für Astronomie, Königstuhl 17, D–69117 Heidelberg, Germany*

[8]*Radio Astronomy Laboratory, University of California at Berkeley, CA 94720, USA*

[9]*Sterrenkundig Instituut Anton Pannekoek, University of Amsterdam, Kruislaan 403, NL–1098 Amsterdam, The Netherlands*

[10]*School of Physics and Astronomy, Cardiff University, 5 The Parade, Cardiff, Wales CF24 3YB, UK*

[11]*UK Astronomy Technology Centre, Royal Observatory Edinburgh, Blackford Hill, Edinburgh EH9 3HJ, UK*

[12]*Space Science and Technology Department, Rutherford Appleton Laboratory, Oxfordshire, OX11 0QX, UK*

[13]*Dept of Astronomy, Stockholm University, AlbaNova University Center, Roslagstullsbacken 21, 10691 Stockholm, Sweden*

[14]*Dept. of Physics and Astronomy, University of Denver, Mail Stop 6900, Denver, CO 80208, USA*

[15]*Institut d'Astrophysique et de Géophysique, Allée du 6 août, 17 - Bât. B5c B–4000 Liège 1, Belgium*

[16]*Institut d'Astronomie et d'Astrophysique, Université libre de Bruxelles, CP 226, Boulevard du Triomphe, B-1050 Bruxelles, Belgium*

[17]*Institute for Space Imaging Science, University of Lethbridge, Lethbridge, Alberta, T1J 1B1, Canada*

[18]*Mullard Space Science Laboratory, University College London, Holmbury St. Mary, Dorking, Surrey RH5 6NT, United Kingdom*

[19]*TU Graz, Institute for Computer Graphics and Vision, Inffeldgasse 16/II, A–8010 Graz, Austria*

Abstract. MESS (Mass loss of Evolved StarS) is a *Herschel* Guaranteed Time Key Program that will image about 100, and do spectroscopy of about 50, post-main-sequence objects of all flavours: (post)-AGB stars and planetary nebula, luminous blue variables, Wolf-Rayet star and supernova remnants. In this review the implementation and current status of MESS is outlined, and first results are presented.

1. Introduction

On May 14, 2009 the *ESA* Cornerstone missions *Herschel* (Pilbratt et al. 2010) and *Planck* (Tauber et al. 2010) were lauched succesfully by an Ariane 5 ECA launcher. Approximately 26 minutes after launch *Herschel* was released from the rocket and placed on a trajectory towards the second Lagrangian point of the Sun-Earth system.

The first few months of the mission were used to commission the spacecraft and verify the performance of the instruments and release the various instrument/observing modes for use. Of relevance here are the phases that followed, the Science Demonstration Phase (SDP), were selected observations from the approved Key Programs (KPs) of the released observing modes were executed, and the Routine Science Phase (RSP) which is currently on-going.

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[*]Herschel is an ESA space observatory with science instruments provided by European-led Principal Investigator consortia and with important participation from NASA.

2. The MESS Program

Of the 21 Guaranteed Time and 21 Open Time KPs, two are dedicated to the study of evolved stars, HIFISTARS (Bujarrabal et al., this volume) and MESS (Groenewegen et al. 2011).

The main aims of the MESS program are twofold, namely (1) to study the structure of the circumstellar envelope and time evolution of the mass-loss rate, and (2) to study molecular and solid state features in the spectra of a representative sample of both low- and intermediate- mass and high-mass post-main sequence objects.

Mass-loss is the dominating factor in the post-main sequence evolution of almost all stars. Although it has been studied since the late 1960's, with the advent of infrared astronomy, many basic questions remain unanswered: what is the time evolution of the mass loss rate, what is the geometry of this process and how does this influence the shaping of the nebulae seen around the central stars of PN and LBVs, can we understand the interaction of these winds with the interstellar medium (ISM), what kind of dust species are formed at exactly what location in the wind.

With its improved spatial resolution compared to *ISO* and *Spitzer*, larger field-of-view, better sensitivity, the extension to longer and unexplored wavelength regions, and medium resolution spectrometers, the combination of PACS (Poglitsch et al. 2010) and SPIRE (Griffin et al. 2010) observations have the potential to lead to a significant improvement in our understanding of the mass-loss phenomenon.

With these science themes in mind, the preparation for a Guaranteed Time (GT) Key Program (KP) started in 2003, culminating in the submission and acceptance of the MESS (Mass-loss of Evolved StarS) GTKP in June 2007. It involves PACS GT holders from Belgium, Austria and Germany, the SPIRE *Specialist Astronomy Group* 6, and contributions from the *Herschel Science Centre*, and Mission Scientists. The allocated time is about 300 hours, of which 170h are devoted to imaging and the remaining to spectroscopy.

2.1. Target Selection

Details on the target selection can be found in Groenewegen et al. (2011).

In brief, for the asymptotic giant branch (AGB) stars a sample was chosen to represent the various types of objects, in terms of spectral type (covering the M-subclasses, S-stars, carbon stars), variability type (L, SR, Mira), and mass-loss (from low to extreme). In the selection the *IRAS* CIRR3 flag was considered to avoid regions of high background. Within each subclass, typically the brightest mid-IR objects were chosen. A sample of 30 O-rich AGB stars and RSGs, 9 S-stars, and 37 C-stars will be imaged with PACS, as well as the two post-RSGs (IRC +10 420 and AFGL 2343). A subset of respectively, 11, 2 and 13 AGB/RSG stars will be imaged with SPIRE, as well as R CrB, the prototype of its class. That the PACS and SPIRE target lists are not identical is on the one hand a question of sensitivity–the fluxes are expected to be higher in the PACS wavelength domain–and on the other hand is a question of the available hours of guaranteed time available to the different partners.

The targets for PACS and SPIRE spectroscopy are (with one exception) a subset of the imaging targets. They have been selected to be bright with *IRAS* fluxes $S_{60} \gtrsim 50$ and $S_{100} \gtrsim 40$ Jy, a S/N of ≥ 20 on the continuum is expected over most of the wavelength range (~55 to ~180 μm). A sample of 14 O-rich AGB stars and RSG, 3 S-stars, and 6 C-stars will be observed spectroscopically with PACS, as well as the two post-RSGs.

A subset of respectively, 5 O-rich and 4 C-rich AGB stars and 1 post-RSG star will be observed spectroscopically with SPIRE.

For the post-AGB (P-AGB) and planetary nebulae (PNe), a sample of twenty well-known C- and O-rich P-AGB and PNe will be imaged with PACS, and a subset of 9 with SPIRE. In spectroscopy twenty-three C- and O-rich P-AGB stars and PNe will be observed with PACS, and a subset of 11 with SPIRE, of which 9 are in common with PACS.

Regarding the massive stars to be observed within MESS, PACS photometry will be obtained for several targets among the most representative LBVs (luminous blue variables) (AG Car, HR Car, HD 168625) and Wolf-Rayet nebulae (M 1-67, NGC 6888). These targets represent various types of LBV and WR nebulae at different stages of interaction with the ISM. PACS spectroscopy will be obtained for the brightest nebulae to measure the fine-structure lines and determine the physical conditions and abundances in the ionised gas and/or in the photodissociation region. In total, eight stars will be mapped with PACS, 2 will be observed with PACS spectroscopy and 2 with SPIRE spectroscopy.

Concerning the observation of supernova remnants, PACS and SPIRE photometric and spectroscopic mapping of Cas A, Kepler, Tycho, Crab and 3C 58 (= SN 1181) will be performed.

3. Implementation

3.1. SPIRE Imaging

Each of the evolved star targets will be mapped in "Large Map" mode, with a scan leg length of 30′, a cross-scan length of 30′ and a repetition factor of 3. The 5 SNe remnants will be mapped in the same mode and repetition factor over $32' \times 32'$ to ensure sufficient sky coverage.

One object (the Helix Nebula) is so large that it will be observed in SPIRE-PACS parallel mode over an area of about 75′ squared.

3.2. SPIRE Spectroscopy

A single pointing FTS observation will be obtained for each of the evolved star targets, with sparse image sampling. The high+low spectral resolution setting will be used, with a repetition factor of 17 for each mode.

For the Cas A supernova remnant, FTS spectroscopy in high resolution mode will be obtained at three positions on the remnant, each sparsely sampling the 2.6′ field of view of the FTS, with a repetition factor of 24. Similar spectra will be obtained for one pointing position only for each of the Crab and Tycho supernova remnants.

3.3. PACS Imaging

All PACS imaging is done using the "scan map" astronomical observation request (AOR) with the "medium" scan speed. Our observations are always the concatenation of 2 AORs (a scan and an orthogonal cross-scan).

The P-AGB and PNe objects will be imaged at 70 and 160 μm. The size of the maps range from about 4 to 9 arcmin on a side with a repetition factor of 6-8. The five

SNe remnants will be observed with 22′ scan-leg lengths at 70, 100 and 160 μm with an repetition factor of 2. The AGB objects will be imaged at 70 and 160 μm and the scan-length varies between 6 and 34′. Repetition factors between 2 and 8 are used.

3.4. PACS Spectroscopy

All PACS spectroscopy is performed by concatenating one (or more) (B2A+short R1) and (B2B+long R1) AORs to cover the full PACS wavelength range from about 54 to 210 μm with Nyquist wavelength sampling. The observing mode is pointed with chopping/nodding with a medium chopper throw of 3′.

Four sources were submitted as SDP targets for PACS spectroscopy, but three (NGC 7027, VY CMa and CW Leo) happened to be observed already as part of the PV of the AORs. These data were officially "transferred" to the MESS program. Two of these sources (VY CMa and CW Leo) were observed in mapping mode. All details over these maps can be found in Royer et al. (2010) and Decin et al. (2010b) respectively.

Nine positions on the Cas A supernova remnant will be observed with the PACS IFU, obtaining full spectral coverage using the (B2A+short R1) and (B2B+long R1) AORs and the largest chopper throw. Single positions on each of the Crab, Kepler and Tycho remnants will be observed in the same way.

4. First Results

The results obtained during SDP and the early phases of RSP match and exceed our expectations. Eight papers were published in the A&A special issue and one in *Nature*, the very first based on *Herschel* data, that illustrate well the science that will be pursued.

4.1. Supernova Dust

Barlow et al. (2010) analyse PACS and SPIRE images of the core-collapse SN remnant Cas A to resolve for the first time a cool dust component, with an estimated mass of 0.075 $M_\odot$, significantly lower than previously estimated for this remnant from ground-based sub-millimeter observations but higher than the dust masses derived for nearby extragalactic supernovae from *Spitzer* observations at mid-IR wavelengths.

4.2. The Circumstellar Envelopes

van Hoof et al. (2010) analyse PACS and SPIRE images of the planetary nebula NGC 6720 (the Ring nebula). There is a striking resemblance between the dust distribution and H_2 emission (from ground based data), which appears to be observational evidence that H_2 has been formed on grain surfaces. They conclude that the most plausible scenario is that the H_2 resides in high density knots which were formed after recombination of the gas started when the central star entered the cooling track.

Another main result is on the detached shells around AGB stars that were first revealed by the *IRAS* satellite as objects that showed an excess at 60 μm. Later observations by single-dish (Olofsson et al. 1996) and interferometric millimetre telescopes (Lindqvist et al. 1999; Olofsson et al. 2000) revealed spherical and thin shells emitting in CO (TT Cyg, U Ant, S Sct, R Scl, U Cam), that were interpreted as short phases of high mass loss, probably related to thermal pulses. Kerschbaum et al. (2010) present for the first time resolved (PACS) images of the dust shells around AQ And, U Ant, and TT Cyg, which allows the derivation of the dust temperature at the inner radius.

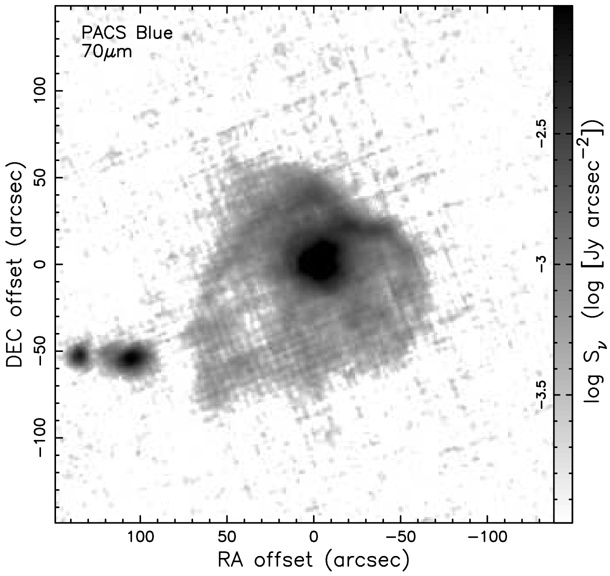

Figure 1. The map of X Her at 70 μm displayed on a logarithmic intensity scale. North is to the top, east to the left. To the south east of X Her there appears to be a pair of interacting galaxies.

Although U Ant and TT Cyg are classical examples of stars surrounded by a detached shell, AQ And was not previously known to have such a shell. Additional examples are presented in Kerschbaum et al. (this volume) and Mecina et al. (this volume).

4.3. Wind-ISM Interaction

Sahai & Chronopoulos (2010) present ultraviolet *GALEX* images of IRC +10 216 (CW Leo) that revealed for the first time a bow shock. Ladjal et al. (2010) demonstrate that the bow shock is also visible in PACS and SPIRE images. The dust associated with the bow shock has a temperature estimated at 25 K. Using the shape of the shock and a published proper motion, a space motion of CW Leo relative to the ISM of $107/\sqrt{n_{\rm ISM}}$ km s^{-1} is derived. A comparison to the models by Wareing et al. (2007) regarding the shape of the bow shock suggests that the space motion is likely to be $\lesssim$ 75 km s^{-1}, implying a local ISM density $\gtrsim$ 2 cm^{-3}. In fact, examples of bow shocks are quite common in the MESS sample. Figure 1 shows the case of X Her (Jorissen et al., in prep.). In this case the flattened shape of the bow shock suggests a larger space motion and/or a larger ISM density compared to CW Leo, or to a highly inclined orientation of the bow shock surface with respect to observers. Additional examples are presented in Jorissen et al. (this volume) and Mayer et al. (this volume).

4.4. Molecular Lines and Chemistry

Regarding spectroscopy, the results published so far illustrate the enormous potential to detect new molecular lines thanks to the increased spectral resolution of PACS w.r.t. *ISO*s LWS and the previously unexplored wavelength region covered by the SPIRE FTS.

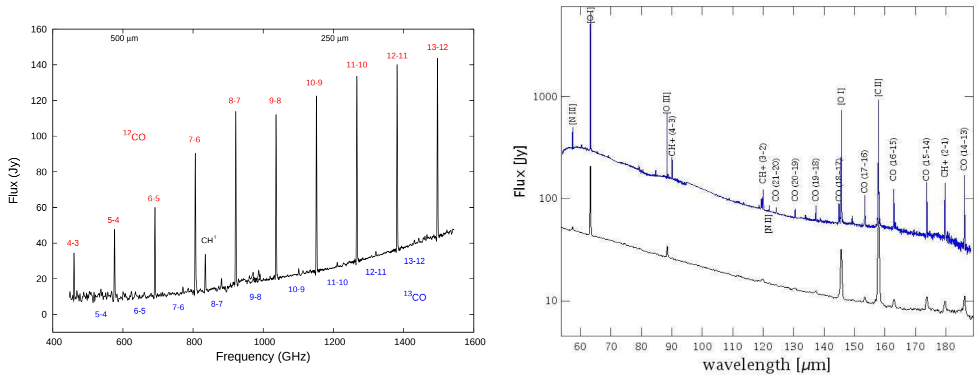

Figure 2. Left panel: SPIRE FTS spectrum of NGC 7027 (Wesson et al. 2010), with ^{12}CO, ^{13}CO and CH^{+} lines indicated. Right Panel: PACS spectrum of NGC 7027 (Exter et al. in prep.; the blue upper curve) with the strongest lines indicated, and the ISO LWS spectrum (black, lower curve) of Liu et al. (1996) scaled by a factor of 0.1 in flux.

Three papers concentrate on CW Leo. Cernicharo et al. (2010) discuss the detection of HCl in this object, and derive an abundance relative to H_2 of 5×10^{-8} and conclude that HCl is produced in the innermost layers of the circumstellar envelope and extends until the molecule is photodissociated by interstellar UV radiation at about 4.5 stellar radii. Decin et al. (2010a) discover tens of lines of SiS and SiO including very high transitions that trace the dust formation zone. A comparison to chemical thermo dynamical equilibrium models puts constrains on the fraction of SiS and SiO that are involved in the dust formation process. The discovery of water a few years ago by Melnick et al. (2001) spurred a lot of interest. Several explantions were put forwards, including the vaporization of icy bodies (comets or dwarf planets) in orbit around the star (Melnick et al. 2001). However the exact origin could so far not be identified as only a single water line was detected. Decin et al. (2010b) analyse SPIRE and PACS spectroscopy and present tens of water lines of both low and high excitation, up to $\sim$ 1000 K. Essentially all propsed mechanisms to explain the presence of water in this star can be refuted. An explanation that is put foward by Decin et al. (2010b) is the penetration of interstellar ultraviolet photons deep into a clumpy CSE initiating an active photo chemistry in the inner envelope.

That water will be a main theme is also illustrated in Royer et al. (2010) who present PACS and SPIRE spectroscopy of the RSG VY CMa. Nine hundred lines are identified, of which half are of water. Finally, Wesson et al. (2010) present SPIRE FTS spectra of three archetypal carbon-rich P-AGB objects, AFGL 618, AFGL 2688 and NGC 7027, with many emission lines detected. Results include the first detection of water in AFGL 2688 and the detection of the fundamental J=1-0 line of CH^{+} in the spectrum of NGC 7027 (see Fig. 2). Fig. 2 also shows the PACS spectrum (based on the central spatial pixel and correcting for the flux loss assuming that the object is a point source) and for comparison the ISO LWS spectrum in Liu et al. (1996) scaled by a factor of 0.1 in flux, illustrating the power of the improved sensitivity and spectral resolution. A full analysis of the PACS spectrum, including a detailed comparison to the LWS spectrum will be presented elsewhere Exter et al. (in prep.).

4.5. Dust Spectroscopy

De Vries et al. (this volume) presents the first result on dust spectroscopy, the detection of the 69 μm Forsterite feature in the P-AGB star HD 161796. Identifying dust features has proven to be perhaps not as easy as originally believed. Reasons are that a more accurate determination of the PACS and SPIRE RSRFs (relative spectral response functions) and improved data reduction techniques are still ongoing, and also the wealth of molecular and fine-structure lines that need to be removed before relatively broad dust features can be identified.

5. Conclusions

The scope, aims and status of the *Herschel* Guaranteed Time Key Program MESS (Mass-loss of Evolved StarS) are presented. The progress of the MESS project can be followed via www.univie.ac.at/space/MESS.

Some of our SDP data is already public and the data taken in routine phase have a proprietary period of one year, implying that data will become succesively public from about December 2010 onwards.

Currently, the PACS maps are produced via the standard `PhotProject` task, that use data that are filtered to remove 1/f-noise as input. We achieve good results for compact objects, but unmasked large-scale structures in the background are affected by the filtering (details on the data reduction can be found in Groenewegen et al. (2011)). In order to improve this, we are currently investigating other filtering and mapping methods, such as MADmap (Cantalupo et al. 2010). That way we also seek to improve the spatial resolution of the final maps. A second point under investigation is to correct the effects caused by the instrument PSF. With its tri-lobe pattern and other wide-stretched features it is currently not possible to make any definite statements about structure in the circumstellar emission close to the central object, although many sources are extended. Thus we are investigating different deconvolution strategies and PSF-related matters. The efforts the MESS consortium are currently undertaking to improve the PACS data processing are described in Ottensamer et al. (this volume).

On the science side, the publication of the very first *Nature* paper based on *Herschel* results by Decin et al. (2010b) is a highlight. It demonstrates the power of the PACS and SPIRE spectrometers. With more than 50 PACS and almost 30 SPIRE targets to be observed spectroscopically this will result in an extremely rich database that, with proper modelling, will allow detailed studies on molecular abundances, the velocity structure in the acceleration zone close to the star, and the mass-loss rate.

On the imaging side the fact that bow shock cases are ubiquitous is extremely interesting. Although this in fact makes it more difficult to derive the mass-loss rate history of the AGB star, it offers an unique opportunity to use these cases as probes of the ISM.

Acknowledgments. JB, LD, KE, AJ, MG, PR, GvdS, SvE, PvH, C.V-N.and BvdB acknowledge support from the Belgian Federal Science Policy Office via de PRODEX Programme of ESA. Y.N. and D.H. are supported by the F.R.S-FNRS. FK and RO acknowledge funding by the Austrian Science Fund FWF under project number I163-N16. PACS has been developed by a consortium of institutes led by MPE (Germany) and including UVIE (Austria); KUL, CSL, IMEC (Belgium); CEA, OAMP (France); MPIA (Germany); IFSI, OAP/AOT, OAA/CAISMI, LENS, SISSA (Italy); IAC (Spain).

This development has been supported by the funding agencies BMVIT (Austria), ESA-PRODEX (Belgium), CEA/CNES (France), DLR (Germany), ASI (Italy), and CICT/MCT (Spain). SPIRE has been developed by a consortium of institutes led by Cardiff Univ. (UK) and including Univ. Lethbridge (Canada); NAOC (China); CEA, LAM (France); IFSI, Univ. Padua (Italy); IAC (Spain); Stockholm Observatory (Sweden); Imperial College London, RAL, UCL-MSSL, UKATC, Univ. Sussex (UK); and Caltech, JPL, NHSC, Univ. Colorado (USA). This development has been supported by national funding agencies: CSA (Canada); NAOC (China); CEA, CNES, CNRS (France); ASI (Italy); MCINN (Spain); SNSB (Sweden); STFC (UK); and NASA (USA).

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