A&A 518, L63 (2010)
DOI: 10.1051/0004-6361/201014547

Herschel: the first science highlights

Astronomy & Astrophysics
Special feature

Letter to the Editor

Herschel-SPIRE observations of the disturbed galaxy NGC 4438⋆

L. Cortese[1], G. J. Bendo[2], A. Boselli[3], J. I. Davies[1], H. L. Gomez[1], M. Pohlen[1], R. Auld[1], M. Baes[4], J. J. Bock[5], M. Bradford[5], V. Buat[3], N. Castro-Rodriguez[6], P. Chanial[7], S. Charlot[8], L. Ciesla[3], D. L. Clements[2], A. Cooray[9], D. Cormier[7], E. Dwek[10], S. A. Eales[1], D. Elbaz[7], M. Galametz[7], F. Galliano[7], W. K. Gear[1], J. Glenn[11], M. Griffin[1], S. Hony[7], K. G. Isaak[1,11], L. R. Levenson[5], N. Lu[5], S. Madden[7], B. O'Halloran[2], K. Okumura[7], S. Oliver[13], M. J. Page[14], P. Panuzzo[7], A. Papageorgiou[1], T. J. Parkin[15], I. Perez-Fournon[6], N. Rangwala[11], E. E. Rigby[16], H. Roussel[8], A. Rykala[1], N. Sacchi[17], M. Sauvage[7], B. Schulz[18], M. R. P. Schirm[15], M. W. L. Smith[1], L. Spinoglio[17], J. A. Stevens[19], S. Srinivasan[8], M. Symeonidis[14], M. Trichas[2], M. Vaccari[20], L. Vigroux[7], C. D. Wilson[15], H. Wozniak[21], G. S. Wright[22], and W. W. Zeilinger[23]

(Affiliations are available in the online edition)

Received 30 March 2010 / Accepted 15 April 2010

ABSTRACT

We present *Herschel*-SPIRE observations of the perturbed galaxy NGC 4438 in the Virgo cluster. These images reveal the presence of extra-planar dust up to ∼4–5 kpc away from the galaxy's disk. The dust closely follows the distribution of the stripped atomic and molecular hydrogen, supporting the idea that gas and dust are perturbed in a similar fashion by the cluster environment. Interestingly, the extra-planar dust lacks a warm temperature component when compared to the material still present in the disk, explaining why it was missed by previous far-infrared investigations. Our study provides evidence for dust stripping in clusters of galaxies and illustrates the potential of *Herschel* data for our understanding of environmental effects on galaxy evolution.

Key words. galaxies: evolution – galaxies: individual: NGC 4438 – infrared: galaxies – dust, extinction

1. Introduction

Clusters of galaxies are extremely hostile environments for star-forming galaxies. A plethora of observations and numerical simulations have revealed how gravitational and hydrodynamical interactions can affect cluster spirals (e.g., Boselli & Gavazzi 2006): stars and gas can be stripped, galaxy morphologies can be changed and star formation activity can be enhanced and/or quenched. However, still very little is known about the effects of the environment on the dust content of cluster galaxies. Since the dust is mixed with the interstellar medium (ISM), the common expectation is that the environment should affect the dust in a similar fashion as the gas. However this hypothesis has still to be confirmed observationally. The launch of *Herschel* (Pilbratt et al. 2010) has opened a new era in the study of dust in galaxies. Thanks to its high spatial resolution and sensitivity to all dust components, *Herschel* should be able to determine whether dust is stripped from infalling cluster spirals and dispersed into the intra-cluster medium (ICM).

One of the most dramatic examples of the effects of the environment on nearby galaxies is represented by the disturbed galaxy NGC 4438, in the Virgo cluster. NGC 4438 is a highly HI-deficient early-type spiral showing stellar tails (Kenney et al. 1995; Boselli et al. 2005) and extra-planar gas (Vollmer et al. 2009). Numerical simulations show that only a combination of ram-pressure stripping and tidal interactions is able to reproduce the disturbed morphology and kinematics of NGC 4438 (Vollmer et al. 2005). However, while Combes et al. (1988) and Vollmer et al. (2005) invoked a high-velocity (∼800 km s^{-1}) gravitational interaction with the companion early-type galaxy NGC 4435, Kenney et al. (2008) have revealed the presence of a series of Hα+[NII] filaments connecting NGC 4438 to the giant elliptical M 86 (see Fig. 1). These new observations favour a more complex scenario in which NGC 4438 has recently (∼100 Myr ago) interacted with M 86 (Kenney et al. 2008). Although the detailed history of NGC 4438 is still unclear, its peculiar properties make it an ideal target to test the power of *Herschel* in unveiling the effects of the environment on the dust properties of cluster galaxies.

In this Letter we present *Herschel*-SPIRE (Griffin et al. 2010) observations of NGC 4438 obtained as part of the *Herschel* science demonstration (SD) phase. The observations of the elliptical galaxy M 86 are presented in a companion paper (Gomez et al. 2010). We assume for NGC 4438 a distance of 17 Mpc (Gavazzi et al. 1999), corresponding to a linear scale of 82 pc/″.

2. Observations and data reduction

The region around NGC 4438 was observed by the *Herschel*-SPIRE instrument as part of the SD observations for the *Herschel* Reference Survey (Boselli et al. 2010a). Eight pairs of cross-linked scan-map observations were carried out over an

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

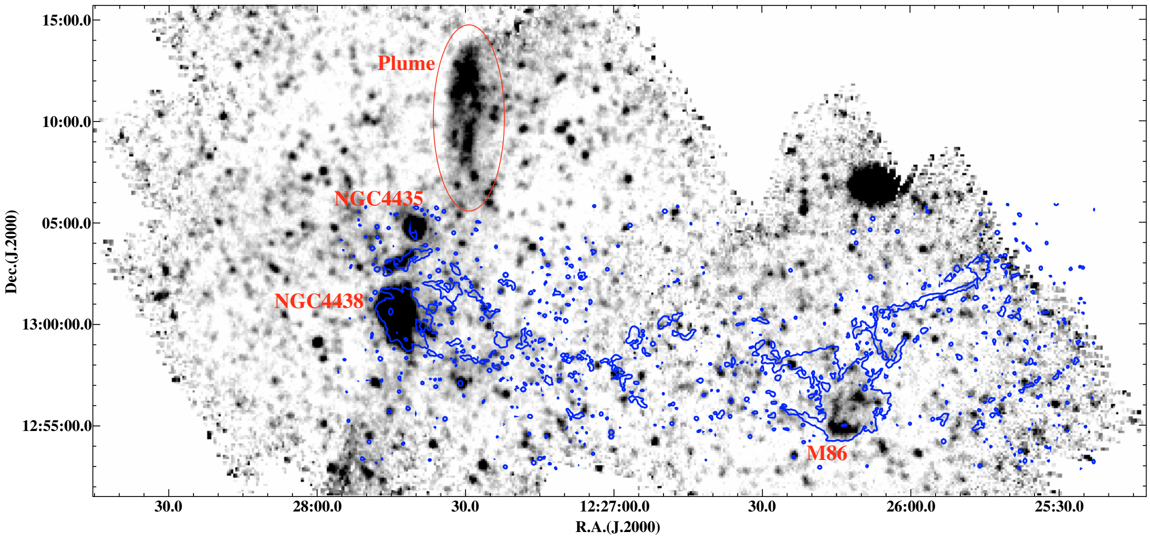

Fig. 1. The NGC 4438/M 86 region as seen by SPIRE. This mosaic is obtained by combining the 250 μm maps centered on NGC 4438 and M 86 (Gomez et al. 2010). The blue contours show the extended Hα+[NII] filaments discovered by Kenney et al. (2008). Note that the intensity excess south of NGC 4438 (near the edge of the frame) is just a residual of the baseline subtraction.

area of $\sim 12' \times 12'$ with a nominal scan speed of $30''$/sec. The data have been reduced following the procedure described in Pohlen et al. (2010) and Bendo et al. (2010a). However, since in this case the median baseline of the whole time line (prior to the de-striper) left some residual large-scale gradients (see Pohlen et al. 2010), we preferred an alternative baseline subtraction on a scan by scan basis. A robust linear fit with outlier rejection was applied to the first and last fifty sample points of the time line for each bolometer, thus avoiding the galaxies and the extended diffuse emission present across the field. The SPIRE astronomical calibration methods and accuracy are outlined in Swinyard et al. (2010). Since at the time of the data reduction the SPIRE pipeline used a preliminary flux calibration, we followed the recommendation of the SPIRE Instrument Control Center and multiplied the flux densities by 1.02, 1.05, and 0.94 at 250, 350, and 500 μm, respectively[1]. The images have flux calibration uncertainties of 15% and the rms are $\sim$5.5, 5.8, 6.9 mJy/beam at 250, 350 and 500 μm, respectively. We note that in all three bands the noise is dominated by confusion. The astrometric uncertainty is $\sim 2''$ and the full widths at half maximum of the SPIRE beams are $18.1''$, $25.2''$, $36.9''$ at 250, 350 and 500 μm, respectively.

3. Results

In Fig. 1 we show a mosaic of the 250 μm SPIRE maps of NGC 4438 and M 86 (Gomez et al. 2010). In addition to NGC 4438, also the companion S0 galaxy NGC 4435 is clearly detected in all the three SPIRE bands. This is not surprising since Panuzzo et al. (2007) showed that this galaxy has just experienced a burst of star formation and it is confirmed by the fact that the SPIRE flux density ratios ($f(250)/f(350) \sim 2.9$ and $f(350)/f(500) \sim 2.6$) are consistent with the values observed in star-forming galaxies (Boselli et al. 2010b).

More intriguing is the presence of a few bright (i.e., peak $f(250) \geq 0.05$ Jy/beam) extended sources possibly associated with NGC 4438. The most remarkable feature is the extended emission to the N-NW of NGC 4435 (Plume in Fig. 1). This plume is approximately $8'$ long and $3'$ wide and it is detected (at least in part) in all the three SPIRE bands. Although its origin (i.e., Galactic or extragalactic) is still debated, Cortese et al. (2010a) have recently shown that the properties of this plume are more consistent with Galactic cirrus than tidal debris at the distance of the Virgo cluster.

Two additional elongated structures (E1 and E2 in Fig. 2) are detected within the optical radius of NGC 4438. E1 appears as a tail extending from the bulge of NGC 4438. However a careful comparison of the SPIRE data with *Spitzer* images reveals that it is just the result of blending of point sources visible at 3.6 and 24 μm, possibly background galaxies. This seems also supported by the lack of any counterpart in UV, HI or Hα+[NII]. Less clear is the origin of E2, which is composed of three different knots. The southern and central knots coincide with an HI cloud discovered by Hota et al. (2007) and the whole feature apparently follows one of the Hα+[NII] filaments pointing towards M 86 (Kenney et al. 2008), suggesting that it might be associated with NGC 4438 (see Fig. 2). If so, this would represent a unique example of stripped intra-cluster dust. However, caution is required before interpreting E2 as a dust stream in Virgo. Firstly, the southern knot is offset ($\sim 15''$ north) from the Hα+[NII] stream, thus it is not clear whether the two features are related. Secondly, *Spitzer* 3.6 and 24 μm point sources are found within $\sim$6-9$''$ from each of the three knots, thus we cannot completely exclude the possibility that E2 is just the result of blending of background sources, like E1. So, although E2 is a very intriguing system, only future investigations will reveal whether it is associated with NGC 4438. We note that, in this case, E2 would represent the only case of submillimetre (submm) emission associated with the intra-cluster Hα+[NII] streams connecting M 86 and NGC 4438 (see also Gomez et al. 2010).

Stronger evidence supporting dust stripping is found in the main body of NGC 4438. In Fig. 2 we compare the distribution of the cold dust as revealed by *Herschel* with those of stars, hot/warm dust and warm ionized[2], cold atomic and molecular hydrogen. Interestingly, despite the presence of a young

[1] See also http://herschel.esac.esa.int/SDP_wkshops/presentations/IR/3_Griffin_SPIRE_SDP2009.pdf

[2] We note that the Hα+[NII] in NGC 4438 and the stripped filaments is likely not tracing star formation but gas cooling after shocks (Kenney et al. 1995; Machacek et al. 2004; Vollmer et al. 2009).

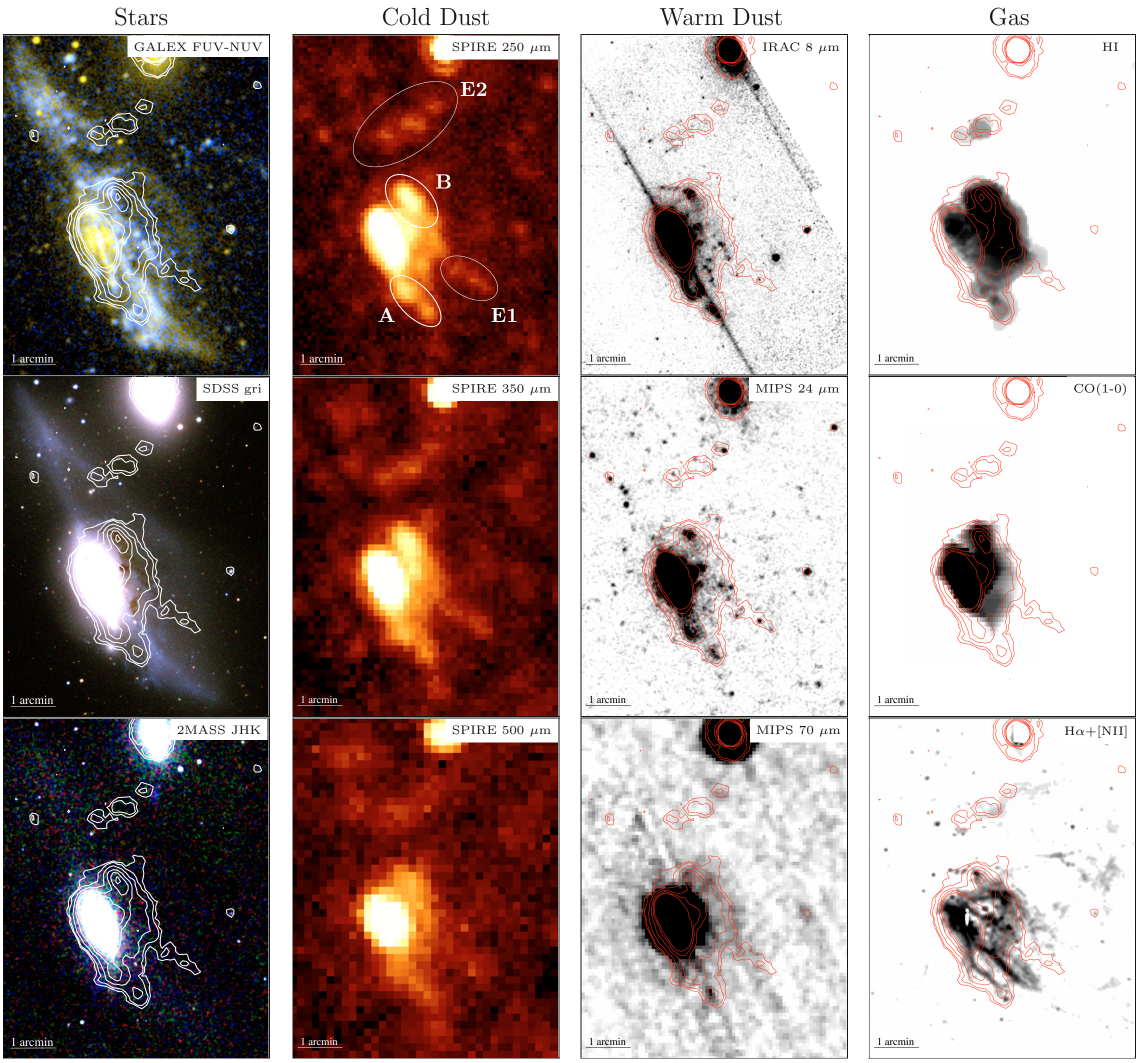

Fig. 2. A panchromatic view of NGC 4438. Each column shows the distribution of a different baryonic component. First column: stars (GALEX UV, SDSS gri, 2MASS *JHK*). Second column: cold dust (SPIRE 250, 350, 500 μm). Third column: warm dust (*Spitzer* 8, 24, 70 μm). Fourth column: cold atomic (HI, Hota et al. 2007), molecular (CO, Vollmer et al. 2005) and warm ionized (Hα+[NII], Kenney et al. 2008) hydrogen. The contours show the 250 μm emission. Contours levels are 0.03, 0.04, 0.07, 0.11, 0.15, 0.19 Jy beam^{-1}. The features discussed in Sect. 3 are highlighted in the 250 μm map.

stellar population, no submm emission is detected in the northern and southern tidal tails. Although the 250–500 μm emission is mainly concentrated within the central ~4.5 kpc of the galaxy, extended emission is visible on the west side of NGC 4438. Particularly remarkable are the two bright regions highlighted in Fig. 2: a tail (A) extending to the south up to ~9 kpc from the center of NGC 4438, and an elongated structure (B) ~4.5 kpc from the plane of the disk and almost completely detached from the main body of NGC 4438.

The tail A is detected at 8, 24, 70 μm and in HI. It extends up the southern stellar tail of NGC 4438 and is composed of at least two disjoint bright knots. Although it follows very closely the southernmost Hα+[NII] filament in NGC 4438, a careful comparison between the 8, 24 μm and Hα+[NII] images reveals that two features do not spatially coincide. The fact that the HI in correspondence of tail A has a recessional velocity ($-40 < V < +20$ km s^{-1}, Hota et al. 2007) significantly lower than the ionized gas ($V \sim -85$ km s^{-1}, Chemin et al. 2005) suggests that the two components might just be projected along the same line-of-sight. Although the presence of submm emission up to the stellar tidal tail is consistent with a dust stripping scenario, it remains uncertain whether tail A is just part of what is left of the disk of NGC 4438 or a stripped dust tail.

In comparison, the formation history of knot B appears a little bit clearer. This feature coincides with the extra-planar dust-lane visible in optical images and it clearly follows the distribution of the extra-planar atomic (Hota et al. 2007) and molecular (Vollmer et al. 2005) hydrogen detected in this region. While the extra-planar CO(1-0) emission is mainly segregated around knot B, the HI extends further south following closely the diffuse 250 μm emission. Although low surface brightness Hα+[NII] emission is observed in correspondence of the diffuse 250 μm to the west of NGC 4438, only a single HII region (slightly offset from the submm emission peak) is observed in knot B. Previous investigations have shown that the disturbed morphology and kinematics of the gas in this region is consistent with a stripping scenario (Kenney et al. 1995; Combes et al. 1988; Vollmer et al. 2005). So, it is likely that we are directly witnessing dust in the process of being removed from the disk of NGC 4438. Contrary to tail A, knot B is not entirely detected by *Spitzer*: only the single HII region and low surface brightness emission are visible at 8 and 24 μm. The integrated $f(350)/f(24)$ flux density ratio of knot B (∼47) is a factor ∼4 higher than the value observed in the main body of NGC 4438, confirming that this feature is missing a warm dust component and it is not associated with active star formation. This is additionally supported by the *reddening* of the $f(250)/f(350)$ ratio (from ∼2.7 to ∼2.1) when moving from the center of NGC 4438 to knot B.

4. Discussion and conclusions

The SPIRE data alone are not sufficient to determine whether the extra-planar dust is in the process of being removed from NGC 4438 or, for example, falling back onto the disk. However, by combining multiwavelength observations with detailed numerical simulations, Vollmer et al. (2005, 2009) have shown that the distribution and kinematics of the different components of the ISM in NGC 4438 can only be reproduced via a combination of tidal interaction and ram-pressure stripping. Although the details of the gravitational interaction are still unclear (i.e., M 86 and/or NGC 4435, Vollmer 2009), it appears that strong on-going ram-pressure (in addition to tidal forces) is necessary to reproduce the properties of the extra-planar gas component in knot B. In this case, whatever the exact mechanisms affecting NGC 4438, it is likely that at least part of the dust in the west side of the galaxy is in the process of being removed from the disk thus providing evidence of dust stripping by environmental effects. If completely removed, the stripped dust will be dispersed in the ICM contributing to its metal enrichment.

Since in galaxies the dust is associated with the gaseous component of the ISM, it is generally expected that when the gas is stripped part of the dust can be removed as well. What is still unclear is how much dust follows the fate of the stripped hydrogen. Unfortunately, the SPIRE fluxes alone are not sufficient to accurately quantify the amount and temperature of the dust in knot B. Nevertheless, we can at least try to estimate the dust mass by using the fluxes at 250 and 350 μm, where knot B is clearly resolved, and assuming $M_{\rm dust} = (f_\nu D^2)/[\kappa_\nu B(\nu, T)]$, where f_ν is the flux density (∼0.98 and ∼0.46 Jy at 250 and 350 μm, respectively), D is the distance and κ_ν is the absorption cross section per mass of dust. We adopt κ_ν=4 and 1.9 cm^2 g^{-1} at 250 and 350 μm respectively (Draine 2003). The total mass of dust in knot B is in the range $\sim 2 \times 10^6$–2×10^7 $M_\odot$ for a dust temperature between 10 and 20 K. In order to determine the total gas mass in the extra-planar cloud, we combined the estimates of M(H$_2$) $\sim 4.7 \times 10^8$ $M_\odot$ (including helium) and M(HI) $\sim 1.5 \times 10^8$ $M_\odot$ obtained by Vollmer et al. (2005) and Hota et al. (2007), respectively. The total gas-to-dust ratio of knot B is in the range ∼30–300, not significantly different from the values observed in nearby galaxies (e.g., Draine et al. 2007; Galliano et al. 2008) and across the disk of star-forming spirals (e.g., Muñoz-Mateos et al. 2009; Bendo et al. 2010b; Pohlen et al. 2010). This seems to support a scenario in which a cloud of gas does not lose a significant amount of its heavy elements when removed from the disk. It is in fact quite remarkable how well the cold dust follows the spatial distribution of the cold hydrogen across the whole galaxy, even in such a highly perturbed system like NGC 4438.

Interestingly, the high degree of spatial correlation between cold dust and cold hydrogen in NGC 4438 is different from what is observed by *Herschel* in M 86 (Gomez et al. 2010). In M 86 the dust is mainly associated with the Hα+[NII] emitting gas and only mildly correlated with the cold atomic component. This is intriguing and might suggest different dust properties (e.g., stripping mechanism, heating source, etc.) in the two galaxies.

Finally, we note that it is unclear whether the extra-planar dust is missing a hot component just because the interstellar radiation field outside the plane is not strong enough to keep it hot, or if the cloud was already dominated by a cold dust component while in the disk. Although the $f(250)/f(350)$ flux ratio is lower than the value observed in the central part of NGC 4438, it is not significantly different from what is observed in the outer parts of the disk of M81 (Bendo et al. 2010a), M 99 and M 100 (Pohlen et al. 2010).

In summary, in this paper we provide evidence for dust stripping by environmental effects in NGC 4438. The high spatial resolution and sensitivity to cold dust of the SPIRE camera allowed us to discover an extra-planar cold dust component completely missed by previous far-infrared surveys. The strong spatial correlation between cold dust, atomic and molecular hydrogen suggests that when the gas is removed also the dust is pulled out the galactic disk. These results provide interesting insights into the evolution of an extreme case among perturbed cluster galaxies. Once combined with the discovery of truncated dust disks in HI-deficient Virgo cluster spirals (Cortese et al. 2010b), our analysis clearly highlights the great potential of *Herschel* for our understanding of the effects of the cluster environment on the dust properties of galaxies.

Acknowledgements. We thank Ananda Hota, Jeff Kenney and Bernd Vollmer for providing us with an electronic version of their data. SPIRE has been developed by a consortium of institutes led by Cardiff University (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); Stockholm Observatory (Sweden); STFC (UK); and NASA (USA).

References

Bendo, G. J., et al. 2010a, A&A, 518, L65
Bendo, G. J., Wilson, C. D., Warrent, B. E., et al. 2010b, MNRAS, 402, 1409
Boselli, A., Boissier, S., Cortese, L., et al. 2005, ApJ, 623, L13
Boselli, A., Eales, S., Cortese, L., et al. 2010a, PASP, 122, 261
Boselli, A., et al. 2010b, A&A, 518, L61
Boselli, A., & Gavazzi, G. 2006, PASP, 118, 517
Chemin, L., Cayatte, V., Balkowski, C., et al. 2005, A&A, 436, 469
Combes, F., Dupraz, C., Casoli, F., & Pagani, L. 1988, A&A, 203, L9
Cortese, L., Bendo, G. J., Isaak, K. G., Davies, J. I., & Kent, B. R. 2010a, MNRAS, 403, L26
Cortese, L., et al. 2010b, A&A, 518, L49
Draine, B. T. 2003, ARA&A, 41, 241
Draine, B. T., Dale, D. A., Bendo, G., et al. 2007, ApJ, 663, 866
Galliano, F., Dwek, E., Chanial, P. 2008, ApJ, 672, 214
Gavazzi, G., Boselli, A., Scodeggio, M., Pierini, D., Belsole, E. 1999, MNRAS, 304, 595
Gomez, H., et al. 2010, A&A, 518, L45
Griffin, M. J., et al. 2010, A&A, 518, L3
Hota, A., Saikia, D. J., & Irwin, J. A. 2007, MNRAS, 380, 1009
Kenney, J. D. P., Rubin, V. C., Planesas, P., & Young, J. S. 1995, ApJ, 438, 135
Kenney, J. D. P., Tal, T., Crowl, H. H., Feldmeier, J., & Jacoby, G. H. 2008, ApJ, 687, L69
Machacek, M. E., Jones, C., & Forman, W. R. 2004, ApJ, 610, 183
Muñoz-Mateos, J. C., Gil de Paz, A., Boissier, S., et al. 2009, ApJ, 701, 1965
Panuzzo, P., Vega, O., Bressan, A., et al. 2007, ApJ, 656, 206
Pilbratt, G. L., et al. 2010, A&A, 518, L1
Pohlen, M., et al. 2010, A&A, 518, L72
Swinyard, B. M., et al. 2010, A&A, 518, L4
Vollmer, B. 2009, A&A, 502, 427
Vollmer, B., Braine, J., Combes, F., & Sofue, Y. 2005, A&A, 441, 473
Vollmer, B., Soida, M., Chung, A., et al. 2009, A&A, 496, 669

Page 5 is available in the electronic edition of the journal at http://www.aanda.org

[1] School of Physics and Astronomy, Cardiff University, Queens Buildings The Parade, Cardiff CF24 3AA, UK
e-mail: luca.cortese@astro.cf.ac.uk
[2] Astrophysics Group, Imperial College, Blackett Laboratory, Prince Consort Road, London SW7 2AZ, UK
[3] Laboratoire d'Astrophysique de Marseille, UMR6110 CNRS, 38 rue F. Joliot-Curie, 13388 Marseille France
[4] Sterrenkundig Observatorium, Universiteit Gent, Krijgslaan 281 S9, 9000 Gent, Belgium
[5] Jet Propulsion Laboratory, Pasadena, CA 91109, United States; Department of Astronomy, California Institute of Technology, Pasadena, CA 91125, USA
[6] Instituto de Astrofísica de Canarias, vía Láctea S/N, 38200 La Laguna, Spain
[7] CEA, Laboratoire AIM, Irfu/SAp, Orme des Merisiers, 91191 Gif-sur-Yvette, France
[8] Institut d'Astrophysique de Paris, UMR7095 CNRS, Université Pierre & Marie Curie, 98 bis Boulevard Arago, 75014 Paris, France
[9] Department of Physics & Astronomy, University of California, Irvine, CA 92697, USA
[10] Observational Cosmology Lab, Code 665, NASA Goddard Space Flight Center Greenbelt, MD 20771, USA
e-mail: Eli.Dwek@nasa.gov
[11] Department of Astrophysical and Planetary Sciences, CASA CB-389, University of Colorado, Boulder, CO 80309, USA
[12] ESA Astrophysics Missions Division, ESTEC, PO Box 299, 2200 AG Noordwijk, The Netherlands
[13] Astronomy Centre, Department of Physics and Astronomy, University of Sussex, UK
[14] Mullard Space Science Laboratory, University College London, Holmbury St Mary, Dorking, Surrey RH5 6NT, UK
[15] Dept. of Physics & Astronomy, McMaster University, Hamilton, Ontario, L8S 4M1, Canada
[16] School of Physics & Astronomy, University of Nottingham, University Park, Nottingham NG7 2RD, UK
[17] Istituto di Fisica dello Spazio Interplanetario, INAF, via del Fosso del Cavaliere 100, 00133 Roma, Italy
[18] Infrared Processing and Analysis Center, California Institute of Technology, Mail Code 100-22, 770 South Wilson Av, Pasadena, CA 91125, USA
[19] Centre for Astrophysics Research, Science and Technology Research Centre, University of Hertfordshire, College Lane, Herts AL10 9AB, UK
[20] University of Padova, Department of Astronomy, Vicolo Osservatorio 3, 35122 Padova, Italy
[21] Observatoire Astronomique de Strasbourg, UMR 7550 Université de Strasbourg - CNRS, 11, rue de l'Université, 67000 Strasbourg
[22] UK Astronomy Technology Center, Royal Observatory Edinburgh, Edinburgh, EH9 3HJ, UK
[23] Institut für Astronomie, Universität Wien, Türkenschanzstr. 17, 1180 Wien, Austria