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Herschel: the first science highlights

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Letter to the Editor

The *Herschel* Virgo Cluster Survey

II. Truncated dust disks in H I-deficient spirals*

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ABSTRACT

By combining *Herschel*-SPIRE observations obtained as part of the *Herschel* Virgo Cluster Survey with 21 cm HI data from the literature, we investigate the role of the cluster environment on the dust content of Virgo spiral galaxies. We show for the first time that the extent of the dust disk is significantly reduced in HI-deficient galaxies, following remarkably well the observed "truncation" of the HI disk. The ratio of the submillimetre-to-optical diameter correlates with the HI-deficiency, suggesting that the cluster environment is able to strip dust as well as gas. These results provide important insights not only into the evolution of cluster galaxies but also into the metal enrichment of the intra-cluster medium.

Key words. galaxies: evolution – galaxies: clusters: individual: Virgo – infrared: galaxies – dust, extinction

1. Introduction

It is now well established that the evolution of spiral galaxies significantly depends on the environment they inhabit. The reduction in the star formation rate (e.g., Lewis et al. 2002) and atomic hydrogen (HI) content (e.g., Giovanelli & Haynes 1985) of galaxies when moving from low- to high-density environments indicates that clusters are extremely hostile places for star-forming galaxies. However, a detailed knowledge of the effects of the environment on all the components of the interstellar medium (ISM) is still lacking. Particularly important is our understanding of how the environment is able to affect the dust content of cluster spirals. Dust plays an important role in the process of star formation, since it acts as a catalyzer for the formation of molecular hydrogen (H_2, from which stars are formed) and prevents its dissociation by the interstellar radiation field. Thus, the stripping of dust might significantly affect the properties of the ISM in infalling cluster spirals.

Since dust is generally associated with the cold gas component of the ISM, it is expected that when the HI is stripped part of the dust will be removed as well, but no definitive evidence of a reduced dust content in cluster galaxies has been found so far. For a fixed morphological type, HI-deficient galaxies[1] appear to have higher IRAS $f(100\ \mu\text{m})/f(60\ \mu\text{m})$ flux density ratios (i.e., colder dust temperatures, Bicay & Giovanelli 1987) and lower far-infrared (FIR) flux densities per unit optical area (Doyon & Joseph 1989) than gas-rich galaxies. However, by using ISO observations of the Virgo cluster (Tuffs et al. 2002), Popescu et al. (2002) find no strong variation with cluster-centric distance in the dust properties of each morphological type. Only the most extreme HI-deficient galaxies appear to be lacking a cold dust component. More recently, Boselli & Gavazzi (2006) have revealed an interesting trend of decreasing dust masses per unit of H-band luminosity with decreasing distance from the center of Virgo. Thus, it is still an open issue whether or not dust is removed from infalling cluster spirals.

The launch of *Herschel* (Pilbratt et al. 2010) has opened a new era in the study of environmental effects on dust. Thanks to its high spatial resolution and sensitivity to all dust components, *Herschel* will be able to determine if cluster galaxies have lost a significant amount of their dust content. Ideally, this analysis should be done on a large, statistically complete sample, following the same criteria used to define the HI-deficiency parameter (Haynes & Giovanelli 1984): i.e., by comparing the dust content of galaxies of the same morphological type but in different environments. By observing a significant fraction (~64 deg^2) of the Virgo cluster at 100, 160, 250, 350 and 500 μm, the *Herschel* Virgo Cluster Survey (HeViCS, Davies et al. 2010, hereafter Paper I; see also `http://www.hevics.org`) will soon provide the optimal sample for such an investigation. In the meantime, with the first HeViCS data it is possible to use a more indirect approach and compare the extent of the dust disk in gas-rich and gas-poor cluster galaxies. Since previous studies have shown that the HI stripping is associated with a "truncation"[2] of the gas (Cayatte et al. 1994) and star-forming disk

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[1] The HI-deficiency (def_{HI}) is defined as the difference, in logarithmic units, between the observed HI mass and the value expected from an isolated galaxy with the same morphological type and optical diameter (Haynes & Giovanelli 1984).

[2] The term "truncation" is used here to indicate either an abrupt steepening of the surface-brightness profile or, more simply, a significant reduction in the disk scale-length compared to the optical one.

(Koopmann & Kenney 2004; Catinella et al. 2005; Boselli & Gavazzi 2006), if the dust follows the atomic hydrogen we should find a reduction in the extent of the dust disk with increasing HI-deficiency.

In this paper we will take advantage of the HeViCS observations, obtained as part of the *Herschel* science demonstration (SD) phase, to investigate the correlation between the dust distribution and gas content in cluster galaxies.

2. Observations and data reduction

A $\sim 245' \times 230'$ field in the center of the Virgo cluster has been observed by *Herschel* using the SPIRE/PACS (Griffin et al. 2010; Poglitsch et al. 2010) parallel scan-map mode as part of the SD observations for HeViCS. In this paper we will focus our attention on the 3 SPIRE bands only. The full widths at half maximum of the SPIRE beams are 18.1, 25.2, 36.9 arcsec at 250, 350 and 500 μm, respectively. Details about the observations and data reduction can be found in Paper I. The typical rms noise across the whole image are $\sim$12, 10, 12 mJy/beam at 250, 350 and 500 μm, respectively (i.e., $\sim$2 times higher than the confusion noise). No spatial filtering is applied during the data reduction, making SPIRE maps ideal to investigate extended submillimetre (submm) emission. The uncertainty in the flux calibration is of the order of 15%.

In order to investigate how the dust distribution varies with the degree of HI-deficiency in Virgo spirals, we restricted our analysis to the 15 spiral galaxies in the HeViCS SD field for which HI surface density profiles are available. The HI maps are obtained from the recent "VLA Imaging of Virgo in Atomic gas" (VIVA) survey (Chung et al. 2009, 13 galaxies: NGC 4294, NGC 4299, NGC 4330, NGC 4351, NGC 4380, NGC 4388, NGC 4402, NGC 4424, NGC 4501, NGC 4567, NGC 4568, NGC 4569, NGC 4579), from Cayatte et al. (1994, NGC4438) and from Warmels (1988, NGC4413). HI-deficiencies have been determined following the prescription presented in Chung et al. (2009). This method is slightly different from the original definition presented by Haynes & Giovanelli (1984), as it assumes a mean HI mass-diameter relation, regardless of the morphological type. Following Chung et al. (2009), we use the difference between the type-dependent and type-independent definitions as uncertainty in the HI-deficiency parameter. We note that, on average, this value is smaller than the intrinsic scatter of $\mathrm{def_{HI}}$ for field galaxies ($\sim$0.27, Fumagalli et al. 2009).

Surface brightness profiles in the three SPIRE bands were derived using the IRAF task ELLIPSE. The center was fixed to the galaxy's optical center (taken from the NASA/IPAC Extragalactic Database[3]) and the ellipticity and position angle to the same values adopted for the HI profiles taken from the literature (Chung et al. 2009; Cayatte et al. 1994; Warmels 1988). The sky background was determined within rectangular regions around the galaxy and subtracted from the images before performing the ellipse fitting. Each profile was then corrected to the "face-on" value using the inclinations taken from the literature. All the galaxies in our sample are clearly resolved in all the three SPIRE bands: e.g., on average $\sim$4–5 beam sizes at 500 μm. Submm isophotal radii were determined at 6.7×10^{-5}, 3.4×10^{-5} and 1.7×10^{-5} Jy arcsec^{-2} surface brightness level in 250, 350 and 500 μm respectively. These are the average surface brightnesses observed at the optical radius (25 mag arcsec^{-2} in B band, de Vaucouleurs et al. 1991) in the four non HI-deficient galaxies ($\mathrm{def_{HI}} < 0.3$) in our sample (NGC 4294, 4299, 4351, 4567) and correspond to $\sim 2-3\sigma$ noise level. Of course, this choice is rather arbitrary and it has no real physical basis. However, as discussed in Sect. 3, the result does not depend on the way in which the isophotal radii have been defined. Although many of our galaxies show some evidence of nuclear activity, we do not find a single case in which the nuclear submm emission dominates the emission from the disk (see also Sauvage et al. 2010). Thus, the isophotal radius is a fair indication of the extent of the dust disk.

3. Results and discussion

In Fig. 1 we compare the optical, 250 μm and HI maps for a subsample of our galaxies with different levels of HI-deficiency. In highly deficient spirals the 250 μm emission is significantly less extended than the optical, following remarkably well the observed "truncation" of the HI disk[4]. This is confirmed in Fig. 2, where we show the ratio of the submm-to-optical isophotal diameters as a function of $\mathrm{def_{HI}}$ for the 15 galaxies in our sample. For all the three SPIRE bands we find a strong correlation (Spearman correlation coefficient $r_s \sim -0.87$, corresponding to a probability $P(r > r_s) > 99.9\%$ that the two variables are correlated) between the submm-to-optical diameter ratio and $\mathrm{def_{HI}}$. Although qualitatively supported by Fig. 1, this correlation alone does not imply a change in the shape of the submm profile. A decrease in the central submm surface brightness of gas-poor galaxies could produce a similar trend without the need to invoke a reduction in the disk scale-length. However, Figs. 3 and 4 clearly exclude such a scenario. In Fig. 3 we show that, while the 350 μm flux per unit of 350 μm area (i.e., the average submm surface brightness) is nearly constant across the whole sample, the 350 μm flux per unit of optical area significantly decreases with increasing $\mathrm{def_{HI}}$. This is even more evident in Fig. 4 where the average surface brightness profiles in bins of normalized radius for gas-rich and gas-poor galaxies ($\mathrm{def_{HI}} > 0.96$; i.e., NGC 4380, NGC 4388, NGC 4424, NGC 4438, NGC 4569) are shown. While the central surface brightness is approximately the same, the profile of HI-deficient galaxies is steeper than in normal galaxies and falls below our detection limit at approximately half the optical radius[5]. We can thus conclude that HI-deficient galaxies have submm disks significantly less extended than the optical disks, following closely the "truncation" observed in HI. Interestingly, from Figs. 2 and 3 it emerges that the extent of the dust disk is significantly reduced compared to the optical disk only for high HI-deficiencies ($\mathrm{def_{HI}} \gtrsim 0.8-1$), i.e. when the atomic hydrogen starts to be stripped from inside the optical radius.

We now need to consider whether we are just observing a trend due to a different mix of morphologies between gas-rich and gas-poor galaxies. Although HI-deficient systems are of earlier type than gas-rich spirals, our result does not change if we focus our attention on Sa-Sbc galaxies only (i.e., 80% of our sample). Since in this range the average 850 μm scale-length-to-optical radius (Thomas et al. 2004) and HI-to-optical radius (Cayatte et al. 1994) ratios do not vary significantly (i.e., less than 1σ) with galaxy type, morphology alone cannot be responsible for the correlations shown in Figs. 2 and 3. Moreover, all the highly HI-deficient galaxies in our sample are well known perturbed Virgo spirals, on which the influence of the cluster

[3] http://nedwww.ipac.caltech.edu/

[4] See also Pohlen et al. (2010) for an analysis of the two grand design Virgo spirals NGC 4254 ($\mathrm{def_{HI}} \sim -0.10$) and NGC 4321 ($\mathrm{def_{HI}} \sim 0.35$).

[5] This also confirms that the correlation shown in Fig. 2 is not qualitatively affected by the definition of submm isophotal radius adopted here.

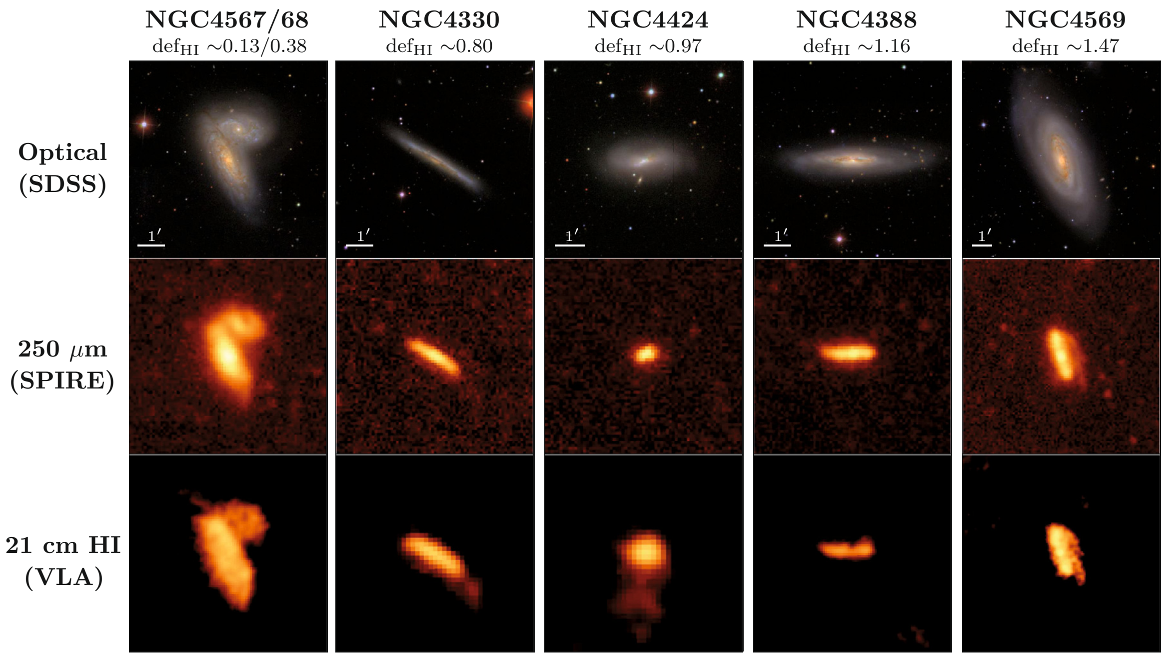

Fig. 1. The optical (*top*), 250 μm (*middle*) and HI (*bottom*) maps for galaxies in our sample with different degrees of HI-deficiency.

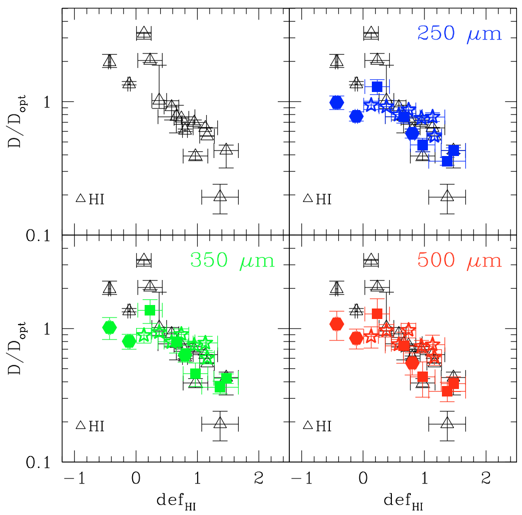

Fig. 2. The ratio of the submm-to-optical diameters versus HI-deficiency in the three SPIRE bands. Squares are for Sa-Sab, stars for Sb-Sbc and hexagons for Sc and later types. For comparison, the triangles show the same relation for the HI-to-optical diameter ratio, where the HI isophotal diameters are taken at a surface density level of 1 $M_{\odot}$ pc^{-2} (Chung et al. 2009).

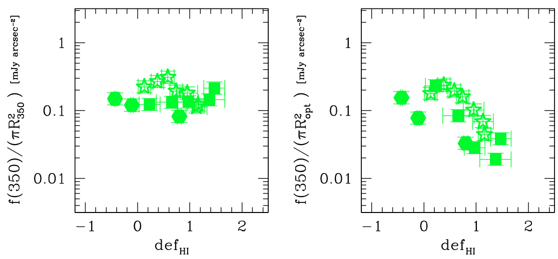

Fig. 3. The 350 μm flux per unit of 350 μm area (*left*) and optical area (*right*) versus HI-deficiency. Symbols are as in Fig. 2.

environment has already been proven (e.g., Vollmer 2009). So, the difference in the dust distribution between gas-poor and gas-rich spirals observed here is likely due to the effect of the cluster environment and is not just related to the intrinsic properties of each galaxy. Future analysis of a larger and more complete sample will allow us to further disentangle the role of environment from morphology on the dust distribution in nearby spirals.

A "truncation" in the surface brightness profile of NGC 4569 (the most HI-deficient galaxy in our sample) has already been observed at *Spitzer* 24 and 70 μm by Boselli et al. (2006). However, while a reduction in the 24 and 70 μm surface brightness might just be a direct consequence of the quenching of the star formation in gas-poor galaxies, this scenario is not valid in our case. For $\lambda \gtrsim 100-200\,\mu$m, the dust emission does not come predominantly from grains directly heated by photons associated with star formation activity, but from a colder component heated by photons of the diffuse interstellar radiation field (e.g., Chini et al. 1986; Draine et al. 2007; Bendo et al. 2010). Since this colder component dominates the dust mass budget in galaxies, the trends here observed are likely not due to a reduction in the intensity of the ultraviolet radiation field, but they imply that in HI-deficient galaxies the dust surface density in the outer parts of the disk is significantly lower than in normal spirals.

An alternative way to compare the properties of normal and gas-poor Virgo spirals is to look at their submm-to-near-infrared colours. Since the K-band is an ideal proxy for the stellar mass and the SPIRE fluxes provide an indication of the total dust mass, it is interesting to investigate how the $f(250)/f(K)$ and $f(500)/f(K)$ flux density ratios vary with def$_{\rm HI}$. We find that highly HI-deficient galaxies have $f(250)/f(K)$ and $f(500)/f(K)$ ratios a factor ~2–3 lower than normal galaxies (Fig. 5). This provides additional support to a scenario in which gas-poor galaxies have also lost a significant fraction of their original dust content.

By comparing the dust mass per unit of H-band luminosity for a sample of late-type galaxies in the Coma-Abell1367 supercluster, Contursi et al. (2001) find no significant difference in the dust content of normal and HI-deficient spirals, apparently in contrast with our results. However, such a difference is due (at least in part) to the fact that the sample used by

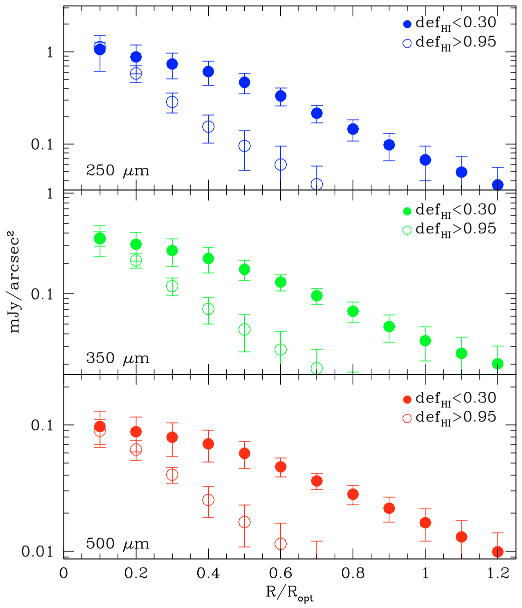

Fig. 4. Average submm surface-brightness profiles in bins of normalized radius for normal and highly HI-deficient galaxies.

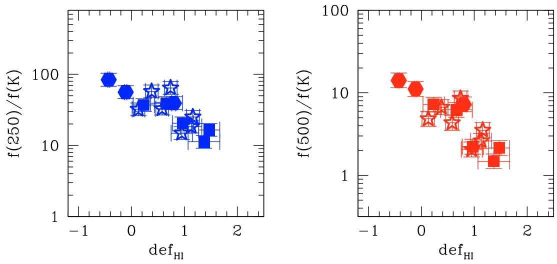

Fig. 5. The 250 μm-to-K-band (*left*) and 500 μm-to-K-band flux density ratios versus HI-deficiency. Symbols are as in Fig. 2.

Contursi et al. (2001) does not include any galaxy with def$_{\rm HI} > 0.87$. It is easy to see in Fig. 5 that, for def$_{\rm HI} < 0.87$, almost no trend is observed between the $f(500)/f(K)$ (or $f(250)/f(K)$) flux density ratio and def$_{\rm HI}$. In fact, the Spearman correlation coefficient drops from $r_s \sim -0.78$ to ~ -0.28 and ~ -0.11 (i.e., a drop in the probability that two variables are correlated to 80 and 40%) for the $f(250)/f(K)$ and $f(500)/f(K)$ ratios, respectively. This implies that the two variables are no longer significantly correlated, highlighting once more that substantial dust stripping is observed only if the ISM is removed from well within the optical radius.

4. Conclusions

In this paper, we have shown that in HI-deficient galaxies the dust disk is significantly less extended than in gas-rich systems. This result, combined with the evidence that HI-deficient objects show a reduction in their submm-to-K-band flux density ratios, suggests that when the atomic hydrogen is stripped part of the dust is removed as well. However, the dust stripping appears efficient only when very gas-poor spirals are considered, implying that in order to be significant the stripping has to occur well within the optical radius. This is consistent with Thomas et al. (2004) who found that the 850 μm scale-length of nearby galaxies is smaller than the HI, suggesting that outside the optical radius the gas-to-dust ratio is higher than in the inner parts.

Our analysis provides evidence that the cluster environment is able to significantly alter the dust properties of infalling spirals. We note that this has only been possible thanks to the unique spatial resolution and high sensitivity in detecting cold dust provided by the *Herschel*-SPIRE instrument and to the wide range of HI-deficiencies covered by our sample. Once combined with the direct detection of stripped dust presented by Cortese et al. (2010) and Gomez et al. (2010), our results highlight dust stripping by environmental effects as an important mechanism for injecting dust grains into the intra-cluster medium, thus contributing to its metal enrichment. This is consistent with numerical simulations which predict that ram pressure alone can already contribute ~10% of the enrichment of the ICM in clusters (Domainko et al. 2006). Interestingly, the stripped grains should survive in the hot ICM long enough to be observed (Popescu et al. 2000; Clemens et al. 2010).

Once completed, HeViCS will allow a search for additional evidence of dust stripping and place important constraints on the amount of intra-cluster dust present in Virgo. Moreover, in combination with the *Herschel* Reference Survey (Boselli et al. 2010b), it will be eventually possible to accurately quantify the degree of dust-deficiency in Virgo spirals.

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References

Bendo, G. J., et al. 2010, A&A, 518, L65
Bicay, M. D., & Giovanelli, R. 1987, ApJ, 321, 645
Boselli, A., & Gavazzi, G. 2006, PASP, 118, 517
Boselli, A., Boissier, S., Cortese, L., et al. 2006, ApJ, 651, 811
Boselli, A., et al. 2010a, A&A, 518, L61
Boselli, A., Eales, S., Cortese, L., et al. 2010b, PASP, 122, 261
Catinella, B., Haynes, M. P., & Giovanelli, R. 2005, AJ, 130, 1037
Cayatte, V., Kotanyi, C., Balkowski, C., & van Gorkom, J. H. 1994, AJ, 107, 1003
Chini, R., Kruegel, E., & Kreysa, E. 1986, A&A, 167, 315
Chung, A., van Gorkom, J. H., Kenney, J. D. P., Crowl, H., & Vollmer, B. 2009, AJ, 138, 1741
Clemens, M. S., et al. 2010, A&A, 518, L50
Contursi, A., Boselli, A., Gavazzi, G., et al. 2001, A&A, 365, 11
Cortese, L., et al. 2010, A&A, 518, L63
Davies, J. I., et al. 2010, A&A, 518, L48
de Vaucouleurs, G., de Vaucouleurs, A., Corwin, Jr., H. G., et al. 1991, Third Reference Catalogue of Bright Galaxies, ed. d. V. e. a. Roman, de Vaucouleurs
Domainko, W., Mair, M., Kapferer, W., et al. 2006, A&A, 452, 795
Doyon, R., & Joseph, R. D. 1989, MNRAS, 239, 347
Draine, B. T., Dale, D. A., Bendo, G., et al. 2007, ApJ, 663, 866
Fumagalli, M., Krumholz, M. R., Prochaska, J. X., Gavazzi, G., & Boselli, A. 2009, ApJ, 697, 1811
Giovanelli, R., & Haynes, M. P. 1985, ApJ, 292, 404
Gomez, H. L., et al. 2010, A&A, 518, L45
Griffin, M. J., et al. 2010, A&A, 518, L3
Haynes, M. P., & Giovanelli, R. 1984, AJ, 89, 758
Koopmann, R. A., & Kenney, J. D. P. 2004, ApJ, 613, 866
Lewis, I., Balogh, M., De Propris, R., et al. 2002, MNRAS, 334, 673
Pilbratt, G. L., et al. 2010, A&A, 518, L1
Poglitsch, A., et al. 2010, A&A, 518, L2
Pohlen, M., et al. 2010, A&A, 518, L72
Popescu, C. C., Tuffs, R. J., Fischera, J., & Völk, H. 2000, A&A, 354, 480
Popescu, C. C., Tuffs, R. J., Völk, H., Pierini, D., & Madore, B. F. 2002, ApJ, 567, 221
Sauvage, M., et al. 2010, A&A, 518, L64
Thomas, H. C., Alexander, P., Clemens, M. S., et al. 2004, MNRAS, 351, 362
Tuffs, R. J., Popescu, C. C., Pierini, D., et al. 2002, ApJS, 139, 37
Vollmer, B. 2009, A&A, 502, 427
Warmels, R. H. 1988, A&AS, 72, 427

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