LETTER TO THE EDITOR

The Herschel Lensing Survey (HLS): Overview

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ABSTRACT

The Herschel Lensing Survey (HLS) will conduct deep PACS and SPIRE imaging of ~40 massive clusters of galaxies. The strong gravitational lensing power of these clusters will enable us to penetrate through the confusion noise, which sets the ultimate limit on our ability to probe the universe with Herschel. Here, we present an overview of our survey and a summary of the major results from our Science Demonstration Phase (SDP) observations of the Bullet Cluster (\(z = 0.297\)). The SDP data are rich, allowing us to study not only the background high-redshift galaxies (e.g., strongly lensed and distorted galaxies at \(z = 2.8\) and 3.2) but also the properties of cluster-member galaxies. Our preliminary analysis shows a great diversity of far-infrared/submillimetre spectral energy distributions (SEDs), indicating that we have much to learn with Herschel about the properties of galaxy SEDs. We have also detected the Sunyaev-Zel’dovich (SZ) effect increment with the SPIRE data. The success of this SDP program demonstrates the great potential of the Herschel Lensing Survey to produce exciting results in a variety of science areas.

Key words. Infrared: galaxies – Submillimeter: galaxies – Galaxies: evolution – Galaxies: high-redshift – Galaxies: clusters: general

1. Introduction

With the successful launch and commissioning of the ESA’s Herschel Space Observatory (Pilbratt et al. 2010), we are again on the verge of making great new discoveries. Following the breakthrough submillimeter/millimeter observations with SCUBA and MAMBO (e.g., Blain et al. 2002), deep MIPS 24 \(\mu\)m observations carried out by the Spitzer Space Telescope have enabled us to trace the evolution of infrared-luminous galaxies up to \(z \approx 3–4\) (e.g., Pérez-González et al. 2005; Le Floc’h et al. 2005). However, the validity of all these Spitzer-based results rests on the assumption that the total infrared luminosities of high-redshift infrared galaxies can be estimated accurately by sampling their rest-frame mid-infrared emission (e.g., the MIPS 24\(\mu\)m band samples the rest-frame 8 \(\mu\)m emission at \(z = 2\)). Indeed, some Spitzer results have already questioned this assumption, suggesting that the use of local galaxy spectral energy distribution (SED) templates may lead to overestimating the total infrared luminosities of high-redshift galaxies (e.g., Papovich et al. 2005, Rigby et al. 2008). Herschel will allow us to measure the total infrared luminosities of a large number of high-redshift galaxies directly for the first time.

With Herschel, confusion noise produced by a sea of blended faint galaxies sets the ultimate limit on how deeply we can probe the Universe. Once the source confusion sets in, it is no longer possible to improve the detection limit by integrating longer. This limitation is especially severe for SPIRE, which reaches the confusion limit quickly.

To penetrate through the confusion limit, gravitational lensing by massive galaxy clusters offers a very powerful and yet cheap solution (e.g., Blain 1997). Magnification factors of 2–4x are quite common in the cluster core regions, and when a background source is strongly lensed (i.e., multiply imaged), magnification factors can reach 10x–30x or more. Note that a magnification factor of 10x corresponds to a factor of 100x saving in observing time when the sensitivity is background-limited. Therefore, a fairly short-integration image of a cluster core region would often reveal sources that are well below the detection limit of an ultra-deep blank-field image. This method was for example employed for the first SCUBA observations of the high-redshift Universe, which resulted in the identification of the substantial population of infrared-luminous galaxies at \(z > 1\) (Smail et al. 1997).

The use of gravitational lensing is especially powerful at infrared/submillimetre wavelengths. This is because cluster cores are dominated by early-type galaxies, which usually emit little at these wavelengths. Therefore, infrared/submillimetre sources detected in cluster cores are often background galaxies. In other words, when observed at these wavelengths, massive cluster cores virtually act as a transparent lens. Lensing studies in the infrared/submillimetre also benefits from the steep galaxy counts at these wavelengths.

These types of lensing surveys, however, have one limitation: the small number of strongly lensed galaxies observed per cluster. Although a large number of massive clusters have been targeted by ground-based submillimetre/millimeter observations...
(e.g., Smail et al. 2002; Chapman et al. 2002; Knudsen et al. 2008), the number of strongly lensed (i.e., multiply imaged) galaxies discovered in these surveys remains small: for example, the \( z = 2.5 \) galaxy in Abell 2218 (Kneib et al. 2004), the \( z = 2.9 \) galaxy in MS0451.6-0305 (Borys et al. 2004), the \( z = 2.8 \) galaxy in the Bullet Cluster (Wilson et al. 2008; Gonzalez et al. 2009; Rex et al. 2009; Johansson et al. 2010), and most recently the exceptionally bright \( z = 3.2 \) galaxy in MACSJ2135-010217 (Swinbank et al. 2010). Based on these observations, we empirically estimate the rate of finding such strongly lensed infrared/submillimeter galaxies to be roughly 1 in 10 with the sensitivity of ground submillimeter observations (e.g., SCUBA, LABOCA). Therefore, many tens of clusters need to be observed to study a significant number of strongly lensed galaxies.

2. The Herschel Lensing Survey (HLS)

As a Herschel Open-Time Key Program, we are conducting exactly such a large lensing survey, targeting \( 40 \) massive clusters of galaxies (“The Herschel Lensing Survey (HLS)”, PI - Egami, 272.3 hrs). Together with the PACS and SPIRE Guaranteed-Time teams, which will observe 10 clusters (Altieri et al. 2010; Blain et al. 2010; Posti et al. 2010) at 100 and 160 \( \mu \)m and SPIRE (Griffin et al. 2010) at 250, 350, and 500 \( \mu \)m for a sample of \( 50 \) massive clusters as a legacy of the Herschel mission.

Target Selection — As the targets of the survey, we have chosen the most X-ray-luminous clusters from the ROSAT X-ray all-sky survey assuming that the most X-ray-luminous clusters are also the most massive and therefore the most effective gravitational lenses. The majority of our targets come from the sample of the Local Cluster Substructure Survey (LoCuSS) (e.g., Smith et al. 2010), which adopts the following selection criteria: (1) \( L_X > 2 \times 10^{44} \text{erg/s} \), (2) \( 0.15 < z < 0.3 \), (3) \( N_{HI} < 7 \times 10^{20} \text{cm}^{-2} \), and (4) \( -70 < \delta < 70 \). In addition, some number of clusters with spectacular lensed systems were included in the sample. For the majority of our target clusters, we have well-constrained accurate mass models, which have been constructed through many years of intensive imaging/spectroscopic campaigns with HST, Keck, and VLT telescopes. Other important considerations were the availability of MIPS 24 \( \mu \)m images and accessibility from ALMA for future follow-up observations although these conditions were not always met.

Observing Parameters — Each target cluster is imaged by both PACS (100 and 160 \( \mu \)m) and SPIRE (250, 350, and 500 \( \mu \)m). With PACS, we use the scan-map mode with the medium speed (some early data were taken with the slow speed). The scan leg lengths are 4\( ^\prime \), cross-scan step is 20\( ^\prime \), number of scan legs is 13. Each cluster is observed twice by orthogonal scan maps (map orientation angles of 45\( ^\circ \) and 315\( ^\circ \)) with 18 repetitions each. The total observing time is 4.4 hrs per cluster with an on-source integration time of 1.6 hrs (1500 sec/pixel).

With SPIRE, we use the Large Map mode with the nominal speed. The scan direction was set to Scan Angles A and B. The length and height of the map are set to 4\( ^\prime \), which in practice will produce a map of 17\( ^\prime \times 17\)\( ^\prime \). With 20 repetitions, the total observing time per cluster is 1.7 hrs with an on-source integration time of 0.6 hrs (17 sec/pixel).

Coordinated Programs — The Herschel Lensing Survey is directly coordinated with a few other observing programs. The most important is the Spitzer/IRAC Lensing Survey (PID 60034; “The IRAC Lensing Survey: Achieving JWST Depth with Spitzer”, PI - Egami, 526 hrs), which is one of the Spitzer Warm-Mission Exploration Science programs. This program will obtain deep (5\( \sigma \)/band) Spitzer/IRAC 3.6 and 4.5 \( \mu \)m images of \( \sim 50 \) massive clusters. By design, its target list is highly overlapped with that of the HLS. Deep IRAC images will be essential for identifying optically-faint high-redshift infrared-luminous galaxies as well as for deriving accurate photometric redshifts. In addition, roughly half of the HLS clusters are being imaged by HST/WFC3 through two on-going programs (GO 11592: “Are Low-Luminosity Galaxies Responsible for Reionization?”, PI - Kneib, 43 orbits; MCT: “Through a Lens, Darkly - New Constraints on the Fundamental Components of the Cosmos”, PI - Postman, 524 orbits).

The Herschel Lensing Survey is also closely related to two other Herschel Open-Time Key Programs: “LoCuSS: A Legacy Survey of Galaxy Clusters at z = 0.2” (Smith et al. 2010) and “Constraining the Cold Gas and Dust in Cluster Cooling Flows” (Edge et al. 2010). The former will obtain wide (30\( ^\prime \times 30\)\)\) and shallow PACS 100/160 \( \mu \)m maps of \( \sim 30 \) massive galaxy clusters at \( z \sim 0.2 \), many of which are also targeted by the HLS. Note that the HLS SPIRE maps cover a significant part (the central 17\( ^\prime \times 17\)\) of the LoCuSS PACS maps, leading to a natural collaboration between the two teams. The latter program will study the brightest cluster galaxies (BCGs) in a dozen cooling-flow clusters, and the HLS data will provide PACS/SPIRE photometry for a much larger sample of BCGs.

3. Science Demonstration Target: The Bullet Cluster

In the Science Demonstration Phase (SDP), we observed the Bullet Cluster at \( z = 0.297 \) (1E0657-56=RXCJ 0658.5-5556). The Bullet Cluster was targeted because, (1) there is a strongly lensed bright submillimeter/millimeter galaxy at \( z = 2.8 \) (see the Introduction), (2) it has a large amount of ancillary data (see Appendix A), and (3) it is in the continuous viewing zone of Herschel.

3.1. Data Processing

Raw Herschel data products are reduced using the common pipeline procedures distributed within the Herschel Interactive Processing Environment (HIPE) (Ott 2010). Deviations from the standard routines are described below.

PACS — The PACS observations were affected by erroneous flashes of the calibration lamp at the end of each scan repetition. These high intensity spikes in the detector time-streams were captured by erroneous flashes of the calibration lamp at the end of each scan repetition. The spike and a large fraction of the spikes were removed by a high-pass filter. Before applying the filter, bright sources (> 5 \( \sigma \)) were masked to prevent Fourier ringing about their positions. These sources were selected from an unmasked first-pass

Table 1. The HLS Bullet Cluster Data

| Instrument | FOV (arcmin) | \( \lambda \) (\( \mu \)m) | beam (arcsec) | Depth (5\( \sigma \), mJy) |
|------------|-------------|-----------------|-------------|-----------------|
| PACS       | \(~ 8 \times 8\) | 100             | 7.7         | 5.5\( \pm 0.7 \) |
|            |             | 160             | 12.0        | 10\( \pm 1 \)   |
| SPIRE      | \(~ 17 \times 17\) | 250             | 18          | 12\( \pm 2 \)   |
|            |             | 350             | 25          | 17\( \pm 3 \)   |
|            |             | 500             | 36          | 18\( \pm 4 \)   |
of the 160 μm map, and the allocated mask size was proportional to their significance. High pass filter lengths of 30 and 40 time-stream frames were used for PACS 100/160 μm data respectively. These lengths were selected to minimize residual 1/f noise in the resultant maps without clipping power on the scale of the PSF. The maps incorporate all data observed while the telescope maintained the nominal scan speed (including some turnaround data). The final PACS maps have pixel sizes of 2″ and 3″ (100/160 μm).

SPIRE — In addition to the nominal scan legs (speed = 30″ s⁻¹), we include all turnaround data observed while the telescope is scanning faster than 0.5″ s⁻¹, greatly increasing coverage of the outer regions. Low-frequency drifts in the SPIRE detectors were removed by subtracting the median value of the nominal scan-speed data from each individual scan leg independently. The final SPIRE maps have pixel sizes of 6″, 9″, and 12″ (250/350/500 μm respectively).

The properties of the processed PACS and SPIRE maps are summarized in Table 1.

### 3.2. Overview of the Bullet Cluster SDP Data

Figure 1 shows the PACS and SPIRE images of the Bullet cluster. Also shown are the Chandra, Magellan/IMACS, Spitzer/IRAC & MIPS 24 μm, LABOCA and AzTEC images of the same field (see Appendix A for references). As expected, the MIPS 24 μm observation goes deep enough to detect the counterparts for most of the PACS/SPIRE sources. This means that one immediate goal of Herschel will be to determine the far-infrared SEDs of 24 μm-detected sources. In fact, the MIPS 24 μm image enables us to extract fluxes from confused Herschel sources accurately (Perez-Gonzalez et al. 2010). However, the most interesting type of Herschel sources may be those without 24 μm
counterparts (such a source has not yet been identified in our data).

In the Bullet Cluster field, we have detected two significantly lensed galaxies, one at \( z = 2.79 \) and the other at \( z = 3.24 \) (Rex et al. 2010, Pérez-González et al. 2010). With magnification factors of \( >54 \) and \( 11.3 \) (Paraficz et al. 2010), respectively, their intrinsic total infrared luminosities are \( <5 \times 10^{11}L_\odot \) and \( 3.5 \times 10^{11}L_\odot \), Figure 1 shows the locations of these two and other background galaxies studied. Note that only HLS can detect luminous infrared galaxies (LIRGs; \( 10^{11} < L_{\text{TIR}} < 10^{12} L_\odot \)) at \( z \gtrsim 2-3 \) in both PACS and SPIRE data.

One major result coming out of this SDP program is the diversity of far-infrared/submillimeter SEDs seen with the \( z = 0.3 \) cluster-member galaxies, \( z = 0.35 \) background group galaxies, and higher-redshift field galaxies behind these two galaxy concentrations (Rawle et al. 2010, Rex et al. 2010). This is shown in Figure 2 which compares the total infrared luminosities measured by fitting the Rieke et al. (2009) SED templates to the observed data points (Measured \( L_{\text{TIR}} \)) against the total infrared luminosity classes originally assigned to these SED templates (Template \( L_{\text{TIR}} \)). Although these two luminosities agree for many of the cluster and background group members, Template \( L_{\text{TIR}} \) is significantly lower than Measured \( L_{\text{TIR}} \) for most of the higher-redshift background galaxies. What this means is that the shapes of the infrared/submillimeter SEDs of these galaxies resemble those of lower-luminosity galaxies in the local Universe. This result is consistent with the earlier findings by various Spitzer observations (e.g., Papovich et al. 2007, Rigby et al. 2008). This also implies that these higher-redshift star-forming galaxies have a larger amount of colder dust compared to the local galaxies with similar infrared luminosities.

In the face of this SED difference, what is surprising is the recent finding that the total infrared luminosities can be estimated fairly well (at least up to \( z \sim 1.5 \)) if we use the luminosity-dependent galaxy SED templates as observed locally (Elbaz et al. 2010). We have confirmed this finding with our Bullet Cluster data. Despite this agreement, however, we have also found that the kind of SED mistmatch seen in Figure 2 clearly exists in the data even at \( z < 1 \) (Rex et al. 2010). This suggests that the good match between the observed and 24 \( \mu \)m derived total infrared luminosities does not necessarily mean that the local SED templates are making good fits to the observed SEDs. A more detailed study of a larger sample is required to resolve this issue.

Equally interesting is the discovery of cluster/group-member galaxies that show large deviations in the opposite direction (Rawle et al. 2010). In other words, the SEDs of these galaxies resemble those of higher-luminosity galaxies in the local Universe. These galaxies therefore are likely to have a larger amount of hotter dust and a more pronounced infrared SED peak compared to the local counterparts with similar infrared luminosities. Similar galaxies were also found in other clusters (Pereira et al. 2010, Smith et al. 2010), possibly suggesting that this type of SEDs may be specific to the cluster environment.

Finally, we also report the first detection of the Sunyaev-Zel’dovich (SZ) effect increment at 350 and 500 \( \mu \)m using the SPIRE data (Zemcov et al. 2010). The measurements will allow us to assess the relativistic correction to the SZ effect.

4. Conclusions

The SDP observations of the Bullet Cluster clearly demonstrate the great potential of the HLS in a variety of science areas. With the Herschel observations nearly done, HLS is expected to make a rapid progress in the near future. One immediate interest is whether it can find strongly lensed sources that are bright enough to perform spectroscopy with Herschel. Ultimately, we will construct a definitive sample of \( \sim \)50 lensing clusters with a variety of multi-wavelength data and accurate mass models. Such a data set can be further exploited by future facilities such as ALMA, JWST, SPICA, and ground 30-meter class telescopes.

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### Appendix A: Ancillary Data for the Bullet Cluster

**Table A.1. The Bullet Cluster Ancillary Data**

| Facilities          | Bands                        | Ref. |
|---------------------|------------------------------|------|
|                     | Imaging                      |      |
| Magellan/IMACS      | B, V, R                      | 1    |
| HST/ACS             | F606W, F775W, F850LP         | 2    |
| VLT/HAWK-I          | Y, J                         | 3    |
| *Spitzer*/IRAC      | 3.6, 4.5, 5.8, & 8.0 µm      | 2    |
| *Spitzer*/MIPS      | 24 µm                        | 2    |
| LABLOCA             | 870 µm                       | 4    |
| AzTEC               | 1.1 mm                       | 5    |
|                     | Spectroscopy                 |      |
| Magellan/IMACS      | optical (856 targets)        | 6    |
| Blanco/Hydra        | optical (202 targets)        | 7    |
| VLT FORS            | optical (14 targets)         | 8    |

**References.** (1) Clowe et al. (2006); (2) Gonzalez et al. (2009); (3) J.-G. Cuby, priv. comm.; (4) Johansson et al. (2010); (5) Wilson et al. (2008); (6) Chung et al., in prep; (7) D. Fadda, priv. comm.; (8) J. Richard, priv. comm.