Deep Herschel view of obscured star formation in the Bullet cluster

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Abstract

We use deep, five band (100–500 μm) data from the Herschel Lensing Survey (HLS) to fully constrain the obscured star formation rate, SFR\textsubscript{FIR}, of galaxies in the Bullet cluster (z = 0.296), and a smaller background system (z = 0.35) in the same field. Herschel detects 23 Bullet cluster members with a total SFR\textsubscript{FIR} = 144 ± 14 M\odot yr\textsuperscript{-1}. On average, the background system contains brighter far-infrared (FIR) galaxies, with ~50% higher SFR\textsubscript{FIR} (21 galaxies; 207 ± 9 M\odot yr\textsuperscript{-1}). SFRs extrapolated from 24 μm flux via recent templates (SFR\textsubscript{24 μm}) agree well with SFR\textsubscript{FIR} for ~60% of the cluster galaxies. In the remaining ~40%, SFR\textsubscript{24 μm} underestimates SFR\textsubscript{FIR} due to a significant excess in observed S\textsubscript{160}/S\textsubscript{24} (rest frame S\textsubscript{25}/S\textsubscript{18}) compared to templates of the same FIR luminosity.

Key words. galaxies: clusters: individual: Bullet cluster – galaxies: star formation – infrared: galaxies – submillimeter: galaxies

1. Introduction

In the last decade many studies have attempted to quantify the star formation rate (SFR) within cluster galaxies. Ultraviolet and optical observations have successfully identified trends between unobscured star formation and local environment, suggesting that star formation in cluster core galaxies is generally more quenched (e.g. Kodama et al. 2004; Porter & Raychaudhury 2007). However, star formation can be obscured by dust, which re-emits stellar light in the far-infrared (FIR), peaking at a rest frame λ\textsubscript{0} ∼ 100 μm. Mid-infrared surveys (e.g. Metcalfe et al. 2005; Geach et al. 2006; Fadda et al. 2008) have explored obscured star formation by estimating total FIR luminosity from template spectra. These templates are often based on small numbers of well constrained galaxies, e.g. Rieke et al. (2009).

The PACS (Poglitsch et al. 2010) and SPIRE (Griffin et al. 2010) instruments, onboard the ESA Herschel Space Observatory (Pilbratt et al. 2010), enable unprecedented multiband coverage of the FIR. The Herschel Lensing Survey (HLS; PI: E Egami) consists of 5-band observations (100–500 μm) of 40 nearby clusters (z ∼ 0.2–0.4). Nominally devised to exploit the gravitational lensing effect of massive clusters to observe high redshift galaxies (see Egami et al. 2010, for details on survey design), a useful by-product is deep FIR observations of the clusters themselves. At these redshifts, Herschel photometry spans the peak of the dust component, allowing an accurate constraint of far infrared luminosity, L\textsubscript{FIR}, and hence obscured SFR.

During the Herschel science demonstration phase, HLS observed the Bullet cluster (1E0657–56; z = 0.296). The reason for this choice was two-fold. First, previous studies report bright submillimeter galaxies in the background (e.g. Rex et al. 2009), with HLS analysis presented in Rex et al. (2010). Second, the Bullet cluster is a recent collision of two clusters (Markevitch et al. 2002), offering a unique laboratory for the study of star formation within a dynamic environment. The sub-cluster has conveniently fallen through the main cluster perpendicular to the line of sight (<8′ from the sky plane; Markevitch et al. 2004). Analysis of X-ray emission shows that a supersonic bow shock precedes the hot gas, while the weak lensing mass profile indicates that this X-ray bright component lags behind the subcluster galaxies due to ram pressure (Markevitch et al. 2002; Barrena et al. 2002). A recent mid-infrared study by Chung et al. (2009) concluded that ram pressure from the merger event had no significant impact on the star formation rates of nearby galaxies. We can re-evaluate these previous studies by using Herschel data to constrain L\textsubscript{FIR} directly. In this letter, we present an exploration of obscured star formation in this cluster environment.

2. Observations

2.1. Photometric data

Five band Herschel imaging was obtained using two instruments: PACS (100 160 μm) covering approximately 8′ × 8′ and SPIRE (250 350 500 μm) with a wider ~17′ × 17′ field. We also use Magellan IMACS optical, Spitzer IRAC and MIPS 24 μm
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In the final sample, there are 47 confirmed Bullet cluster members, and an additional 28 sources in the \( z = 0.35 \) system. Of these, 23 and 21 galaxies respectively are detected in the Herschel bands, highlighted by the filled distribution in Fig. 1. The background system has a much higher fraction of Herschel detections than the Bullet cluster (75% of 24 \( \mu m \) sources, compared to 50%).

3. Results and discussion

3.1. Far-infrared (FIR) spectral energy distributions

For each source, the FIR spectral energy distribution (SED) is fit to all available Herschel data points, taking into account the upper limits for non-detections. The dust component is modeled by a modified, single-temperature, blackbody

\[
S_\nu = N(\nu/\nu_0)^\beta B_\nu(T)
\]

where \( S_\nu \) is flux density, \( \beta \) is dust emissivity index (fixed at 1.5; using \( \beta = 2.0 \) would vary \( L_{\text{FIR}} \) by <15% on average) and \( B_\nu(T) \) is the Planck blackbody radiation function for a source at temperature \( T \). The shape of this optically thin (rather than thick) blackbody imitates the inclusion of a secondary (warm) dust component. As we are concerned only with \( L_{\text{FIR}} \) and SFR, the parameterization of the data is the most important aspect, and \( T \) is used purely as a fit parameter. Galaxies within the PACS field have well constrained fits, and \( T \) is allowed to float freely. For those without PACS data (<40%), \( T_0 \) has been forced to a narrow range centered on the mean value from the constrained SEDs (30 ± 1 K). Forcing \( T_0 \) to a similarly narrow range about values ~1σ from the constrained mean, varies \( L_{\text{FIR}} \) by <25%. Bias in \( L_{\text{FIR}} \) due to model priors is comparable in scale to systematics from instrument calibration.

\( L_{\text{FIR}} \) is integrated over (rest frame) \( \lambda_0 = 8–1000 \mu m \) from which \( SFR_{\text{FIR}} \) is derived using the Kennicutt (1998) relation. As an illustration, Fig. 2 displays the FIR SED fits for five of the most luminous galaxies in the sample. These simple fits may underestimates \( L_{\text{FIR}} \) by up to a factor of 1.8 (Rex et al., 2010), as they lack a mid-infrared component. Future analysis will fully account for additional components. For the purposes of this study, a blackbody fit is sufficient. The luminosities of galaxies in the background system have been de-magnified using the Bullet cluster lensing model of Paraficz et al. (in prep.). The remaining figures in this paper present de-magnified values.

3.2. Star formation rates within the systems

The system at \( z = 0.35 \) contains IR galaxies brighter than those in the Bullet cluster, with three galaxies meeting the LIRG criterion \( [\log (L_{\text{FIR}}/L_\odot)] > 11.0 ] \) and an additional two within 1σ. A further 10 members have \( L_{\text{FIR}}/L_\odot > 10.5 \). In contrast, the Bullet cluster contains two LIRGs, and only six other galaxies brighter than \( \log (L_{\text{FIR}}/L_\odot) = 10.5 \).

The total star formation rate of the 23 Bullet cluster galaxies is \( 144 ± 14 M_\odot \text{yr}^{-1} \). The 21 galaxies in the background system are, on average, ~50% more active, with a total \( SFR = 207 ± 9 M_\odot \text{yr}^{-1} \). Only five of these galaxies have been magnified by more than 20%, and the minimum detected SFRs are similar in each system. Therefore, it is unlikely that the higher total SFR is due to a decreased lower limit caused by magnification. The difference is likely to reflect the mass of the systems, although the lower SFR in the Bullet cluster may indicate that cluster-cluster mergers are not important for triggering FIR starbursts.

Figure 3 displays the spatial distribution of the Herschel-derived SFR for the two systems. Flux densities in optical...
are as observed (i.e. not de-magnified). Redshift and, for background system galaxies, magnification factor, \( \mu \), are displayed at the top of each panel. \( L_{\text{FIR}} \) and \( SFR_{\text{FIR}} \) derived from the best fit blackbody (black line) are also shown and have been de-magnified where necessary.

The mid-infrared bands, e.g. MIPS 24 \( \mu \)m, are often used to estimate far infrared luminosity, \( L_{\text{FIR}} \), and hence obscured SFR, via template FIR SEDs such as Rieke et al. (2009). Those authors provide a simple formula (their Eq. (14)) to convert 24 \( \mu \)m flux directly to SFR. The templates are based on local (U)LIRGs (\( z \approx 0.1 \)), and at high redshift, may not be valid. Here, we test the template accuracy for cluster galaxies at \( z = 0.35 \).

### 3.3. 24 \( \mu \)m as a \( L_{\text{FIR}} \) predictor in nearby clusters

The mid-infrared bands, e.g. MIPS 24 \( \mu \)m, are often used to estimate far infrared luminosity, \( L_{\text{FIR}} \), and hence obscured SFR, via template FIR SEDs such as Rieke et al. (2009). Those authors provide a simple formula (their Eq. (14)) to convert 24 \( \mu \)m flux directly to SFR. The templates are based on local (U)LIRGs (\( z \approx 0.1 \)), and at high redshift, may not be valid. Here, we test the template accuracy for cluster galaxies at \( z = 0.35 \).

### 3.2. 24 \( \mu \)m as a \( L_{\text{FIR}} \) predictor in nearby clusters

B-band and 24 \( \mu \)m are shown for comparison. An initial examination suggests that the Bullet cluster exhibits a radial trend in \( SFR_{\text{FIR}} \) (lacking significant FIR detection towards the centre), reminiscent of that found in other contemporary studies (Braglia et al. 2010; Pereira et al. 2010). The gradient in the Bullet cluster SFR is examined in detail in Chung et al. (in prep.).

The IR and optical flux of the background system trace similar distributions, whereas in the Bullet cluster, the B-band flux is more centrally concentrated, away from the IR sources. This may indicate a different trend in dust retention for the two systems. While the 24 \( \mu \)m and Herschel SFR density maps generally trace the same distribution, there are significant outliers: bright 24 \( \mu \)m sources with relatively lower SFRs, and vice versa. In the following section, we compare the SFR estimated from 24 \( \mu \)m (through the Rieke et al. 2009, templates) to the \( SFR_{\text{FIR}} \).

In Sect. 3.2 (Fig. 3), we suggested that while 24 \( \mu \)m flux and \( SFR_{\text{FIR}} \) follow the same general distribution, they are not perfectly correlated. A direct comparison of \( SFR_{\text{FIR}} \) to \( SFR_{24}\mu m \) (Fig. 4; plotted against the dust-peak-mid-IR flux ratio) leads to the same conclusion. For \( \sim 60\% \) of galaxies, the two SFRs agree well. However, there are several galaxies (\( \sim 30\% \)) that have severely underestimated \( SFR_{24}\mu m \), and these also display systematically redder \( S_{100}/S_{24} \). If \( SFR_{\text{FIR}} \) is underestimated by the simple blackbody fits (Sect. 3.1), the \( SFR_{24}\mu m \) predictions are correspondingly worse.

Are the under-predicted \( SFR_{24}\mu m \) caused by the redder \( S_{100}/S_{24} \) colours? Figure 5 examines the Rieke et al. templates more closely, comparing them to the Herschel fluxes. For templates spanning the \( L_{\text{FIR}} \) range of the observations, the agreement is good for \( \lambda_0 \approx 200 \) \( \mu \)m. However, at 100 \( \mu \)m there are 8 significant outliers; we define 100 \( \mu \)m excess galaxies as those with \( S_{100}/S_{24} \) (rest frame) \( > 30 \) as the templates predict \( S_{100}/S_{24} \leq 20 \). Only templates with very high luminosities, i.e. \( \log(L_{\text{FIR}}/L_\odot) \geq 12 \), match the observed \( S_{100}/S_{24} \), but even the brightest sample galaxy has only \( \log(L_{\text{FIR}}/L_\odot) \approx 11.5 \), while most are \( \log(L_{\text{FIR}}/L_\odot) \leq 11 \). Although high \( L_{\text{FIR}} \) templates have \( S_{100}/S_{24} \approx 30 \), their lower peak wavelength leads to an under-prediction at \( \lambda \approx 200 \) \( \mu \)m in at least three observed SEDs. We also compare to the least active Dale & Helou (2002) FIR templates (\( \alpha = 1.8 \rightarrow 2.5 \)). The locus of these are substantially similar to the low luminosity Rieke et al. templates and thus also only
under-predict $S_{100}/S_{24}$. We stress that, unlike $L_{\text{FIR}}$ and $SFR_{\text{FIR}}$, the presence of a 100 $\mu$m excess is independent of the blackbody fits and the systematic uncertainties therein.

Galaxies with a 100 $\mu$m excess account for ~40% of cluster members detected with PACS, and cover the entire range of $L_{\text{FIR}}$ sampled. Above a nominal luminosity limit of $10^{10} L_\odot$, 55% of Bullet cluster galaxies have the 100 $\mu$m excess. The fraction in the background system is lower at 36%. This may indicate a trend with environment, or could be due to the off-centre view of the latter system (i.e., a potential radial trend). High resolution HST imaging covers five of the eight 100 $\mu$m excess galaxies (Fig. 6). Despite the small number, the galaxies span a broad range of types and morphologies. Further examples are required for a firm conclusion, but these suggest that the 100 $\mu$m excess is not due to a single population of galaxies.

The $S_{100}/S_{24}$ colours alone may have led to the conclusion that the 100 $\mu$m excess was due to galaxies with generally colder dust. However, fits to the combined HLS PACS+SPIRE photometry suggest that this is not the case. Rather, the excess may be due to an additional warm dust component or active galactic nuclei (AGN) which are not considered in the templates. Using a simple power law to parameterize flux in the range 24–100 $\mu$m, we estimate the AGN contribution to total bolometric luminosity via the $S_{100}/S_{25}$ indicator for ULIRGs (Veilleux et al. 2009, Fig. 36). None of the 100 $\mu$m excess galaxies have predicted AGN fractions >30%. However, we may be under-predicting the contribution if the mid-IR SED steepens beyond 60 $\mu$m, or if the indicator breaks down for galaxies in this luminosity range.

**Herschel** PACS observations of $z \sim 0.2$ LoCuSS clusters (without the advantage of complementary SPIRE data), display a similar fraction of 100 $\mu$m excess galaxies (Smith et al. 2010; Pereira et al. 2010). However, the high redshift field sample from the HLS Bullet cluster observations (Rex et al. 2010) lacks a comparable excess at $A_0 \approx 75$ $\mu$m. These results suggest that the effect could be either redshift dependent or cluster-specific: HLS is well placed for further analysis of the $S_{100}/S_{24}$ phenomenon, as the combined PACS+SPIRE data ensures that both the excess and entire FIR component can be constrained simultaneously.

### 4. Conclusions

Using deep *Herschel* observations (100–500 $\mu$m) to fully constrain the FIR component, we derive obscured SFRs for galaxies in the Bullet cluster ($z = 0.296$), and a background system ($z = 0.35$) in the same field. *Herschel* detects 23 Bullet cluster members, with a total $SFR_{\text{FIR}} = 144 \pm 14 M_\odot$ yr$^{-1}$, while the background system contains 21 detections but ~50% higher SFR (207 $\pm 9 M_\odot$ yr$^{-1}$). The relative distributions of $SFR_{\text{FIR}}$ and optical flux suggest a difference in dust retention between the two systems. For ~60% of galaxies, $SFR_{\text{FIR}}$ agrees well with estimated SFRs from 24 $\mu$m flux via recent templates. However, the remaining galaxies display a significant excess at 100 $\mu$m ($A_0 \approx 75$ $\mu$m) compared to templates, which causes an under-prediction in $SFR_{24\mu m}$. We note that such an excess is not found in the high redshift, field sample (Rex et al. 2010). Future studies will exploit the full range of 5-band *Herschel* cluster observations available in HLS, to form a more complete understanding of the environmental effect on obscured star formation rates, and explore the origin and dependencies of the 100 $\mu$m excess.

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