Luminosity and Dust Mass Functions of Galaxy Clusters

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ABSTRACT

We have been using *Herschel* data at 100–500 μm to study the far-infrared luminosity functions of Virgo, Coma and Fornax cluster galaxies and to compare them to those of field galaxies. We show that the Virgo cluster lacks the very bright and the numerous faint sources detected in other surveys of the general field carried out by both *Herschel* and *Planck* (typically a luminosity function faint end slope of -1.0 compared to -1.5). We fit the far-infrared spectral energy distributions using a fixed ($\beta = 2$) emissivity index to obtain dust masses and temperatures. The dust mass function has a similar shape to that of the field, so the disparity in cluster and field galaxy luminosity functions must be due to different dust temperatures not different quantities of dust. The Virgo cluster is over dense in dust by about a factor of 100 compared to the field.

1. INTRODUCTION

We are using data from *Herschel* to study the far-infrared luminosity functions of cluster galaxies at 100, 160, 250, 350 and 500 μm. The data comes from the *Herschrel Virgo Cluster Survey* (HeViCS, Davies et al., 2010), the H-ATLAS survey (Coma, Eales et al. 2010) and the *Herschel Fornax Cluster Survey* (HeFoCS, Davies et al. 2013). In this paper we concentrate on the cluster we have made the most progress with, the nearby (17 Mpc) Virgo cluster.

2. DATA

We use as our starting point the *Herschel* data presented and described in Auld et al. (2013). This consists of observations of a total area of 84 sq deg made using *Herschel* in parallel scan map mode to obtain data in five bands (100, 160, 250, 350 and 500 μm). A full discussion of this data and its reduction and calibration are given in Davies et al. (2012) and Auld et al. (2013) and will not be repeated here. The result is the detection at 250 μm of 251 galaxies selected in the optical from the Virgo Cluster Catalogue (VCC, Binggeli et al. 1985). Although it is not ideal to have an optical rather than a far-infrared selected sample we have no other way of ensuring that we have a pure cluster sample rather than one contaminated by background sources. We will show below that there is no evidence for additional cluster far-infrared sources missed by our selection method.

The 251 galaxies listed by Auld et al. (2013) extend in distance (as given in the GOLDMINE database, Gavazzi et al. 2003) from 17 to 32 Mpc with galaxy groupings at 17, 23 and 32 Mpc. This range of 15 Mpc in depth is large for a cluster and much larger than the linear size we survey on the plane of the sky (about 4 Mpc at a distance of 23 Mpc). For this reason in this paper we restrict our analysis to galaxies with distances of 17 and 23 Mpc so that line-of-sight and plane of sky distances are comparable. These distances correspond with those of sub-cluster A containing M87 and sub-cluster B containing M49 (Gavazzi et al. 1999). Restricting distances to between 17 and 23 Mpc leads to a sample of 208 galaxies and a surveyed volume of about 62.4 Mpc^3.

3. LUMINOSITY FUNCTIONS

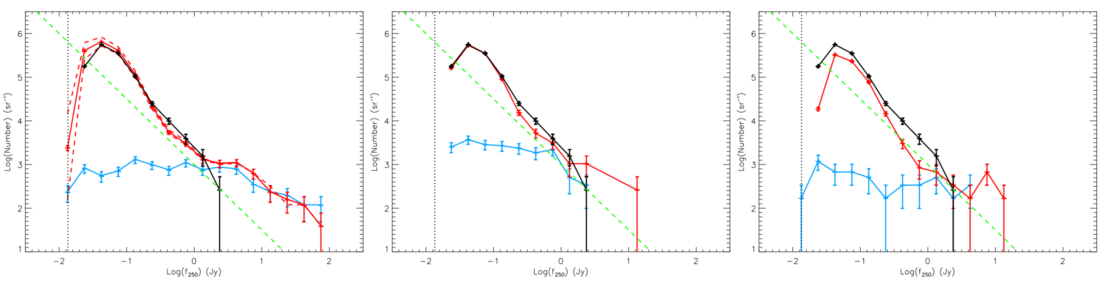

Figure 1. *Top left:* The Virgo field 250 μm faint galaxy number counts (dark grey line) compared to the faint galaxy number counts in the H-ATLAS NGP field (black line). The light grey line shows the number counts using the 207 galaxies from the Auld et al. (2013) data. The diagonal dashed line has a slope of 1.5 and indicates the expected counts for a non-evolving Euclidean universe. The dotted line indicates the minimum flux density detectable given the minimum detection area and 1σ noise level in the NGP data. *Top right:* as for Virgo, but now this is Coma. *Bottom:* as for Virgo, but now this is Fornax.

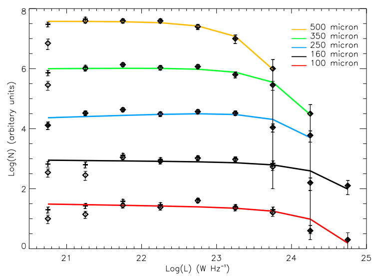

Figure 2. *Virgo cluster galaxy luminosity functions for the 5 Herschel far-infrared bands. The data has been arbitrarily off-set from each other to avoid confusion.*

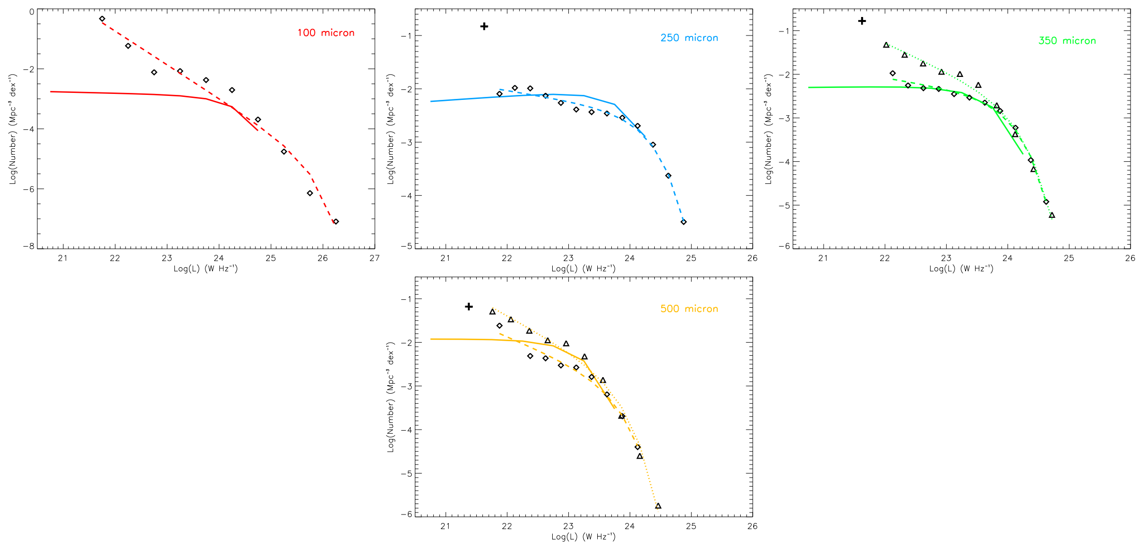

Figure 3. A comparison of luminosity functions at different wavelengths and over different environments. In each case the solid line is taken from Figure 2 (Virgo cluster). *Top left: IRAS* data with fit. *Top right: Herschel* field data with fit. Bottom left - *Herschel* (lower) and *Planck* data (upper) with fits. *Bottom right: Herschel* (lower) and *Planck* data (upper) with fits.

The Auld et al. (2013) data is obtained from the positions of optically selected galaxies in the VCC. This is not ideal as we would prefer to select galaxies via their far-infrared flux density when constructing far-infrared luminosity functions. To address this issue we have carried out a faint galaxy number count analysis of the Virgo field and compared it to the faint galaxy number counts derived from the North Galactic Pole (NGP) field observed by the H-ATLAS consortium (Eales et al. 2010), both at 250 μm. Our motivation for doing this is to compare the number counts from the general field (NGP) with that obtained by 'looking through' the Virgo cluster into the Universe beyond.

The NGP data is fully described in (Valiante et al., in preparation). We have used the source detection programme Sextractor to extract faint sources from both the Virgo and NGP data, taking great care to apply identical methods to both fields. The derived number counts for both the NGP and Virgo fields are shown in Figure 1. The solid black line shows the NGP number counts. The counts are consistent with other counts and detection methods used on previous H-ATLAS data Clements et al. (2010). The important question is whether there is a faint galaxy excess in the Virgo field that might be associated with a far-infrared population not detected using our optical source list. Looking at Figure 1 we can see that below about 1 Jy the black line traces the dark grey line very well and there is no evidence for an excess population over and above that detected by our optical selection.

In Figure 1 (middle and bottom) we also show our preliminary results from carrying out a similar analysis on Coma and Fornax (Fuller et al., in preparation). From these three figures our initial assessment is that the luminosity functions of all three clusters are flatter at the faint end than that of field galaxies. We conclude that there is no good evidence for an additional population of faint far-infrared sources that is not associated with the previously identified optical sources. In Figure 2 we show the derived luminosity functions with the best fitting Schechter functions — fitting parameters are given in Table 1. To illustrate the disparity between the cluster and field, we also show in Table 1 the Schechter fitting parameters for luminosity functions derived by others — see also Figure 3. The *IRAS* 'field' 100 μm data comes the compilation of 629 galaxies in the Bright Galaxy sample of Sanders et al. (2003). The *Herschel* data comes from the H-ATLAS survey (Eales, private communication) using data from the three SPIRE bands at 250, 350 and 500 μm. The *Planck* data is taken directly from Negrello et al. (2013).

The most disparate wavelength between cluster and field is 100 μm, where the *IRAS* luminosity function of nearby bright galaxies is considerably steeper at the faint end than that in the cluster (Sanders et al. 2003). With a slope of $\alpha = -1.0$ our

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Table 1. Schechter function fitting parameters.

Band (μm)	Instrument	Region	α	L^* (10^{24} W Hz^{-1})	ϕ (Mpc^{-3} dex^{-1})
100	*Herschel*	Virgo	-1.0 ± 0.1	2.1 ± 0.6	0.3 ± 0.1
160	*Herschel*	Virgo	-1.0 ± 0.1	2.8 ± 1.0	0.3 ± 0.1
250	*Herschel*	Virgo	-0.9 ± 0.1	0.8 ± 0.2	0.6 ± 0.1
350	*Herschel*	Virgo	-1.0 ± 0.1	0.5 ± 0.1	0.5 ± 0.1
500	*Herschel*	Virgo	-1.0 ± 0.1	0.2 ± 0.01	0.5 ± 0.1
100	*IRAS*	Field	-2.1 ± 0.1	46 ± 15	0.000012 ± 0.000007
250	*Herschel*	Field	-1.19 ± 0.04	1.6 ± 0.1	0.0017 ± 0.0002
350	*Herschel*	Field	-1.22 ± 0.05	0.7 ± 0.1	0.0014 ± 0.0002
500	*Herschel*	Field	-1.58 ± 0.12	0.4 ± 0.1	0.0067 ± 0.0003
350	*Planck*	Field	-1.65 ± 0.08	0.9 ± 0.1	0.0013 ± 0.0003
550	*Planck*	Field	-1.78 ± 0.1	0.4 ± 0.1	0.0010 ± 0.0003

cluster luminosity function either lacks faint dusty galaxies and/or the star formation required to heat the dust. Another noticeable difference between the cluster and the field is the lack of vary luminous infrared sources in the cluster — the derived L^*_{100} for the field is about a factor of 20 higher than in the cluster. With a faint-end slope of $\alpha > -2.0$ the *IRAS* luminosity function is unbound and we cannot calculate a luminosity density ($\rho_{\rm FIR} = \phi L^* \Gamma(2.0 + \alpha)$).

Comparing our Virgo longer wavelength luminosity functions with others, we find that a steeper faint-end slope and a larger value of L^* are a common feature of the field. Eales et al. (private communication) have derived the 250, 350 and 500 μm luminosity functions using H-ATLAS data for galaxies with $z \leq 0.1$ ($D \leq 411$ Mpc). Negrello et al. (2013) have done a similar thing using *Planck* 350 and 550m μ data for galaxies with $D \leq 100$ Mpc, see Table 1. and Figure 3. When comparing the two the *Planck* data gives a steeper faint-end slope, about the same L^* and a luminosity density a factor of about 2 higher than the *Herschel* data. Generally the cluster has a far-infrared luminosity density about two orders of magnitude higher than that of the field.

It is clear that at all far-infrared wavelengths there is a lack of fainter sources in the cluster compared to what is generally found in the local field. There is either a relative lack of emitting dust, it is cold or if far-infrared emission is closely connected to star formation then there is a lack of star formation in low luminosity cluster systems.

4. DUST MASS, TEMPERATURE

We have used the 100–500 μm data to fit modified blackbody curves to the far-infrared spectral energy distributions of the 207 Virgo galaxies. We use a power law dust emissivity $\kappa_\lambda = \kappa_0(\lambda_0/\lambda)^\beta$ with $\kappa_0 = 0.192\,{\rm m^2\,kg^{-1}}$ at λ_0 =350 μm and a fixed $\beta(= 2)$. As discussed in Davies et al. (2012) (see their Figure 6) many galaxy far-infrared spectral energy distributions fit modified blackbodies with $\beta = 2$ very well. Having dust masses for our galaxies we can construct the dust mass function in a similar way to the luminosity functions described earlier (Figure 4). The fitted mass function parameters are given in Table 2. Note that the dust mass function value of M^*_{Dust} is very close to the value recently measured for M31 ($5.4 \times 10^7\,{\rm M_\odot}$) by Draine et al. (2013).

We have also compared our dust mass function parameters with those obtained for the general field by Dunne et al. (2011). The dust mass density is about a factor of 100 higher in the cluster than it is in the field. All three mass functions shown in Figure 4 are essentially flat at the low mass end with no evidence for them being different in this respect between field and cluster. This is in contrast to the luminosity functions which were all steeper in the field than in the cluster. This can only come about if we have generally hotter dust in the lower luminosity field galaxies and so the steepness of the field galaxy luminosity functions must be due to enhanced star formation. We might have expected that if dust stripping processes are important in the cluster environment that the relative numbers of low and high dust mass galaxies may have changed between cluster and field i.e. lower mass galaxies more readily losing their dust, but this does not appear to be so.

5. CONCLUSIONS

- Faint galaxy number counts both on and off the cluster field indicate that the optical selection of galaxies does not miss a population of previously undetected cluster far infrared sources.
- Cluster luminosity functions are generally flatter at the faint end than those derived for field galaxies — the cluster lacks faint far-infrared sources.

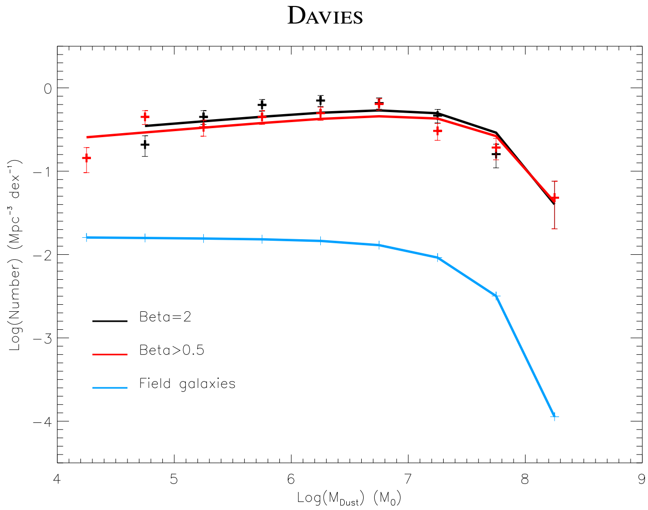

Figure 4. The dust mass function. The black line is for all 207 galaxies which have either measured or predicted flux densities in all five *Herschel* bands and have then been fitted with a $\beta = 2$ model. The blue line is the field galaxy dust mass function taken from Dunne et al. (2011).

Table 2. Schechter function fitting parameters to the Virgo cluster dust mass function. For comparisons we also give the values for the field taken from Dunne et al. (2011).

Sample	α	M^{*}_{Dust} (10^7 $M_{\odot}$)	ϕ (Mpc^{-3} dex^{-1})	ρ_{Dust} (10^7 $M_{\odot}$ Mpc^{-3})
$\beta = 2$	-0.9 ± 0.1	5.7 ± 1.3	0.7 ± 0.1	1.8
Field	-1.0	3.6	0.006	0.02

- The cluster dust mass function has a similar shape to that of field galaxies so the differences in the luminosity functions must be due to temperature — more low dust mass star forming galaxies in the field.
- The cluster is over dense in dust by about a factor of 100 compared to the field.
- Individual galaxies have a range in global dust temperatures similar to that found in different regions of a typical galaxy like M31 (15–25 K).

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