The Comoving Infrared Luminosity Density: Domination of Cold Galaxies across $0 < z < 1$

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ABSTRACT

In this paper we examine the contribution of galaxies with different infrared (IR) spectral energy distributions (SEDs) to the comoving infrared luminosity density, a proxy for the comoving star formation rate (SFR) density. We characterise galaxies as having either a cold or hot IR SED depending upon whether the rest-frame wavelength of their peak IR energy output is above or below 90 µm. Our work is based on a far-IR selected sample both in the local Universe and at high redshift, the former consisting of IRAS 60 µm-selected galaxies at $z < 0.07$ and the latter of Spitzer 70 µm selected galaxies across $0.1 < z \leq 1$. We find that the total IR luminosity densities for each redshift/luminosity bin agree well with results derived from other deep mid/far-IR surveys. At $z < 0.07$ we observe the previously known results: that moderate luminosity galaxies ($L_{IR} < 10^{11} L_\odot$) dominate the total luminosity density and that the fraction of cold galaxies decreases with increasing luminosity, becoming negligible at the highest luminosities. Conversely, above $z = 0.1$ we find that luminous IR galaxies ($L_{IR} > 10^{11} L_\odot$), the majority of which are cold, dominate the IR luminosity density. We therefore infer that cold galaxies dominate the IR luminosity density across the whole $0 < z < 1$ range, hence appear to be the main driver behind the increase in SFR density up to $z \sim 1$ whereas local luminous galaxies are not, on the whole, representative of the high redshift population.

Key words: galaxies: evolution, starburst, infrared: galaxies

1 INTRODUCTION

The rise in the comoving star formation rate (SFR) density up to $z \sim 1$ and its subsequent flattening [Lilly et al. 1996; Madan et al. 1996] has now been well studied at several wavelengths (e.g. Bunker et al. 2004; Hopkins & Beacom 2004, and references therein). While the global picture to $z = 1$ has been well constrained by observation, the details of how or why this change occurs remain largely unknown. There now is evidence that star formation depends on both galaxy mass (Fouliner et al. 2003; Juneau et al. 2003) and environment (Lewis et al. 2002; Elbaz et al. 2007) presenting a more complicated picture of galaxy evolution than simple evolution of the luminosity function.

The infrared (IR), and particularly the far-IR, is one of the most powerful tracers of star formation as IR luminosity directly scales with SFR [Kennicutt 1998, and references therein] and far-IR emission originates from regions of cold dust and gas that constitute the fuel for an ongoing burst of star formation. Another advantage of selecting sources at long wavelengths is the low contribution by active galactic nuclei (AGN), if present, to the total IR luminosity [Alexander et al. 2003; Clements et al. 2008]. Studies of the distant Universe at IR wavelengths remain limited and the most sensitive probe has been surveys with the Spitzer 24 µm band. However, this wavelength is relatively far from the peak of all but the hottest IR galaxies and progressively shifts to shorter wavelengths at higher redshifts where strong spectral features in the observed frame can also complicate matters. The few studies done with deep Spitzer 70 µm imaging have found rapid evolution in the total IR luminosity function [Huynh et al. 2007].

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Magnelli et al. (2009). When the IR luminosity function is integrated at different redshifts it is found that the IR luminosity density increases rapidly up to \( z = 1 \) in a similar fashion to the SFR density. Nevertheless, the relative contribution by luminosity to the IR luminosity density changes with redshift with starbursts (10 \( \leq \log(L_{IR}/L_{\odot}) < 11 \)) dominating locally, but with luminous IR galaxies (LIRGs: 11 \( \leq \log(L_{IR}/L_{\odot}) < 12 \)) and ultra-luminous IR galaxies (ULIRGs: 12 \( \leq \log(L_{IR}/L_{\odot}) < 13 \)) becoming increasing contributors at higher redshifts (Le Floch et al. 2008; Magnelli et al. 2009).

In Symeonidis et al. (2009) hereafter S09 we studied the IR spectral energy distributions (SEDs) of a sample of 70 \( \mu \)m selected galaxies at \( z \geq 0.1 \), using a sample of local, \( z < 0.1 \), IRAS 60 \( \mu \)m selected galaxies for comparison. We fitted the mid to far-IR photometry of both samples with models from Siebenmorgan & Kriigel (2007). We found that the majority of the 70 \( \mu \)m sources had IR SEDs which peaked, in \( \nu \times F_\nu \), at longer wavelengths than galaxies from the local sample with similar luminosities. In the local sample we observed a shift of the IR SED peak to shorter wavelengths with increasing luminosity (as has previously been noted; Sanders & Mirabel 1996; Chapman et al. 2003; Rieke et al. 2009), whereas the 70 \( \mu \)m sample had a wide range of peak wavelengths the distribution of which varied little with luminosity. The observation that the IR SEDs of luminous, distant galaxies were on average different to their local analogues was in contrast to other recent results, Magnelli et al. (e.g. 2009) who concluded there was no significant change in IR SED of luminous galaxies with redshift. Models of galaxy evolution in the IR have tended to assume that the SEDs of high redshift luminous sources follow the luminosity trend seen in local sources (Lagache et al. 2003; Pearson 2003; Le Borgne et al. 2009; Rowan-Robinson 2004). However, as shown in S09, the range of IR SEDs for luminous galaxies is much wider at high redshifts than seen locally.

In this paper we examine the contribution of galaxies with different IR SEDs to the comoving IR luminosity density (IRLD). We will compare our results to earlier work (Le Floch et al. 2003) by examining the contribution to the IRLD by luminosity, but this time with a sample selected at 70 \( \mu \)m rather than 24 \( \mu \)m. This selection enables us to use a more robust selection of IR luminous galaxies as 70 \( \mu \)m lies closer to the peak of typical IR SEDs. Hence, the total IR luminosity can also be estimated more accurately, especially with constraints (mainly detections) from 160 \( \mu \)m data. We examine the IRLD in more detail by focusing on the contribution by IR SED type within each bin. By obtaining an estimate of the peak of the IR SED in rest-frame \( \nu \times F_\nu \), we can characterise these IR bright sources as being either cold or hot depending on whether the SED peaks above or below 90 \( \mu \)m (32.2 K for a blackbody). We choose this wavelength for two reasons. Firstly, local IR galaxies appear to have a warm IR component (\( \lambda \sim 60 \mu \)m) associated with dust around young star forming regions and a cooler “cirrus” component (\( \lambda \geq 100 \mu \)m) associated with more extended dust heated by the interstellar radiation field (Lonsdale & Helou 1987). Secondly, this 90 \( \mu \)m cut also marks a divide between the SEDs of most local ULIRGs and those of cold SMGs seen at high redshift, most of which would be classified as cold by our definition (Chapman et al. 2003). We note that there is a linear relationship between the IRAS colours often used to define the IR galaxies as ‘cold’ or ‘hot’ (e.g. Chapman et al. 2003) and the peak wavelength used in this work.

We present our far-IR galaxy sample in §2, describe our determination of the comoving IRLD in §3. We present our results in §4 and discuss them in §5. Throughout we use the current ‘concordance’ cosmology: \( \Omega_M = 1 - \Omega_\Lambda = 0.3 \), \( \Omega_\Lambda = 1 \), and \( H_0 = 70 \) km s\(^{-1}\) Mpc\(^{-1}\) (Spergel et al. 2003).

2 THE FAR-IR GALAXY SAMPLE

The IR luminous galaxies we use here are taken from the study of S09 who used a local and distant far-IR selected sample. The local sample is the IRAS Bright Galaxy Sample from Sanders et al. (2003) which is selected to have 60 \( \mu \)m flux densities above 5.24 Jy covering the entire sky surveyed by IRAS at Galactic latitudes |\( \delta \)| > 5\(^\circ\). The higher redshift sample we use consists of Spitzer 70 \( \mu \)m galaxies from two well studied extragalactic fields: the Extended Groth Strip (EGS covering \( \sim 0.3^\circ\), Davis et al. 2007) and the 13\(^{th}\) XMM-Newton/Chandra Deep Field (13\(^{th}\) covering \( \sim 0.3^\circ\), Sevmar et al. 2008).

We restrict our 70 \( \mu \)m sample to sources with 0.1 \( \leq z \leq 1.0 \) ruling out local resolved sources at \( z < 0.1 \) and very high redshift sources where there may not be complete redshift information. Although the 13\(^{th}\) field 70 \( \mu \)m sample has complete redshift information (40 spectroscopic and 40 photometricic) the original EGS spectroscopic survey only targeted \( \sim 2/3 \) of candidate sources (Davis et al. 2007). By examining the original EGS 70 \( \mu \)m sample (Symeonidis et al. 2007) we estimate from broad-band colours that 101 sources lie within 0.1 \( \leq z \leq 1.0\), 66 of which have spectra. Hence, in the next section we multiply the area of the EGS by a factor of 66/101 to correct for those sources not included on the assumption these 66 are representative of the parent pop-
The comoving IR luminosity density (IRLD) plotted as a function of redshift in different luminosity bins: starbursts (blue), LIRGs (yellow) and ULIRGs (red). For each bin we plot the total IRLD and the separate contribution from the cold and hot galaxies. The hot and cold points are marginally offset in redshift from the total IRLD for clarity. Derivation of the uncertainties and upper limits found in S09, but the used for the local BGS sample, also using the best fit SED as determined in S09. The same method was determined from fits to models of all the galaxies in the bin. We do not include a bin to cover the highest redshift and at other redshifts we use the Spitzer 70 µm selected sample from S09. We overlay, for comparison, the IRLD derived from deep 24 µm observations by Le Floc’h et al. (2005, shaded regions). We observe a general trend of hot galaxies dominating the local LIRG and ULIRG bins, but the increase in IRLD at higher redshifts is mainly due to an increase in the contribution from cold galaxies rather than hot galaxies.

3 METHOD

We determine the IR luminosity density using a version of the classic $1/V_{\text{max}}$ method (Schmidt 1968; Ehrich 1976). We use the following formula to determine the luminosity density in each redshift/luminosity bin for the 70 µm sample

$$\Phi_{\text{IR}}(L, z) = \Sigma_i (L_i/V_i)$$

where $L_i$ is the total 8 – 1000 µm IR luminosity (in solar units) of a source and $V_i$ is the maximum volume (in Mpc$^3$) a source could occupy given the size of the redshift bins, the area of the survey, our 10 mJy completeness limit and the best fit SED as determined in S09. The same method was used for the local BGS sample, also using the best fit SED found in S09, but the $V_i$ was limited by the 5.24 Jy detection limit at 60 µm and a redshift range of 0.005 ≤ $z$ ≤ 0.07. Uncertainties are determined using the expression:

$$\delta\Phi_{\text{IR}}(L, z) = \sqrt{\Sigma_i (L_i/V_i)^2 + \delta\Phi(\delta L_i)^2}$$

where $V_i$ and $L_i$ are defined as before and the $\delta\Phi(\delta L_i)$ term represents the contribution of the uncertainty in the luminosity of individual sources within that bin (due to photometric redshifts and the modeling in S09). The binning (see Fig. 1) was defined by the definitions of the luminosity class (LIRG etc.) and the desire to have bins of equal size in $\log(1+z)$ space. We do not include a bin to cover the highest redshift LIRGs as our survey is much less sensitive to cold galaxies in this region of parameter space and hence we are unable to derive a representative ratio of hot and cold galaxies. For each luminosity-redshift bin we calculated the total comoving IR luminosity density as well as that for the cold and hot galaxies separately. The redshift used when plotting each bin is the mean redshift of all the sources contributing to that bin in $\log(1+z)$ space. Upper limits for a bin with no cold or hot sources were determined from the 97.72% confidence limit (equivalent to 2 $\sigma$) for a null detection using the volume of the whole bin and the mean luminosity of all the galaxies in the bin.

In S09 we discussed how the construction of our sample might affect the results. The selection of the 70 µm sample at rest-frame 35 – 60 µm means our selection could potentially favour galaxies that peak around those wavelengths, i.e. hot galaxies by our definition, contrary to the increasing fraction of cold galaxies. We also established that the uncertainty in the long-wavelength Spitzer/160 µm photometry did not
have a significant effect on the peak wavelength determined from the SED fitting. The uncertainties on IR luminosity from the SED fitting, when carried over to this work, contribute little to the total uncertainties on individual data points in Fig. 2 i.e. small number statistics dominate.

4 RESULTS

We present the observed comoving IR luminosity density of our sample in Fig. 2 as a function of luminosity and redshift. The total IR luminosity densities at each luminosity-redshift bin are in good agreement with those from Le Floc’h et al. (2005) notwithstanding the potential sample variance between small volumes and the different IR SED models used. The results presented here also broadly agree with those of Magnelli et al. (2009) who base their work on stacking 24 μm sources at longer wavelengths. The largest disagreement with previous work is at z ∼ 0.2 where the total IR luminosity density of the starbursts presented here is about 0.4 dex below the value of Le Floc’h et al. (2005).

Examining the contribution by IR SED to each luminosity-redshift bin, we find that there is significant variation in the relative contribution of cold and hot galaxies with luminosity and redshift. Locally we see cold sources dominating the starburst bin, but at higher luminosities they contribute less; cold galaxies comprise only one third of the LIRG bin and they contribute nothing to the ULIRG bin. The contribution of cold galaxies to the IR luminosity density from starbursts remains fairly constant at 60–70% over the redshift range we can detect them, 0 ≤ z ≤ 0.2. However, for both LIRG and ULIRG bins the contribution from cold galaxies increases considerably at higher redshifts. Cold galaxies become the dominant contributor to the IR luminosity density in these bins above z = 0.1, in contrast to the situation seen in the local Universe. In fact, cold galaxies are responsible for most of the rise with redshift of the IR luminosity density in both the LIRG and ULIRG bins.

In Fig. 3 we plot the fraction of the total IR luminosity density in each redshift/luminosity bin due to cold galaxies. We can see how the contribution of cold galaxies to the starburst luminosity density remains constant up to z ∼ 0.2, although our data here cannot constrain that fraction at higher redshifts. The contribution of cold galaxies to the LIRG and ULIRG luminosity density increases dramatically with redshift; locally the contribution is very low or negligible, but at higher redshift cold galaxies dominate. We find that our results do not change qualitatively if we change our choice of fiducial wavelength (that divides between hot or cold galaxies) by ±10 μm.

5 DISCUSSION

In S09 we demonstrated that the IR SEDs of individual LIRGs and ULIRGs at 0.1 ≤ z ≤ 1.0 peak at longer wavelengths, and span a wider range, than local galaxies at similar luminosities. Other changes in the properties of star forming galaxies have occurred since z ∼ 1. Star formation shifts from massive galaxies at high redshifts to progressively less massive galaxies at lower redshifts (e.g. Cowie et al. 1996; Juneau et al. 2005). A shift is also seen in environment of the most strongly star forming galaxies with star formation tending to occur in over-dense environments at z ∼ 1 (Elbaz et al. 2007), a reverse of the trend seen locally. While the dependence of star formation on stellar mass and environment informs us about the star formation history and potential or current galaxy mergers, information about the IR SED is a direct measure of the physical conditions in galaxies underlying major episodes of star formation.

In this paper we have expanded the results of S09 by deriving IR luminosity densities at different luminosities and epochs. We observe that the total IR luminosity densities derived from a 70 μm sample are broadly consistent with results derived from shorter wavelengths (Fig 3). The low IR luminosity density of the z ∼ 0.2 starburst bin compared to other results is likely due to the effect of sample variance over the small cosmic volume probed. We also separate our sample into galaxies that can be characterised as having cold or hot SEDs and study their contribution to each redshift/luminosity bin. We find two striking new results. Firstly, we observed a rapid change in the make up of LIRG and ULIRG bins: locally they are dominated by hot galaxies, but at z > 0.2 they are dominated by cold galaxies. Secondly, cold galaxies appear to be the dominant contributor to the total IR luminosity density over 0 ≤ z ≤ 1.0; when starburst galaxies dominate at z < 0.2 we find that they are mainly cold and by the time LIRGs and ULIRGs begin to dominate at higher redshifts they are also mainly cold. Hence, a cold mode of star formation has dominated galaxy evolution since z ∼ 1 and is likely responsible for the increase in the star formation rate density up to z = 1.

While Fig. 2 does dramatically show the rise of cold galaxies in the LIRG and ULIRG bins at higher redshifts we note that hot galaxies are still found at those redshifts. In fact the results presented here do not rule out a rise with redshift in the number (and luminosity density) of hot galaxies. Therefore, the distribution of types of SEDs remains quite wide at high redshift. Fig. 3 most strikingly demonstrates the evolution of the relative contribution of cold galaxies to each redshift/luminosity bin. The rise in the contribution of cold galaxies to the LIRG and ULIRG bins is most rapid be-
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between $z \sim 0$ and $z \sim 0.3$. We now consider if AGN could be responsible for the change in the fraction of cold galaxies. As a powerful AGN would make the IR SED hotter the presence of an AGN can not explain the prevalence of cold galaxies at high redshift. AGN could, however, be the cause of the high fraction of hot galaxies locally. Studies have shown that the incidence of AGN are low in local LIRGs, $10 - 20\%$, (Petric et al., 2009, in press), but while it is higher in ULIRGs, $\sim 40\%$ (Farrah et al. 2007) the $8 - 1000 \mu$m IR luminosity remains dominated by star formation. We note that at higher redshift the incidence of AGN, and their contribution to total IR luminosity, also remains low (Alexander et al. 2003; Clements et al. 2008). Hence, AGN are not a significant contributor to the IR luminosity of the sources studied here and therefore are not responsible for any of the trends with redshift.

The prominence of cold galaxies discovered here might suggest that there could be a substantial contribution to the IR emission of luminous galaxies at high redshift from a cold cirrus component akin to that observed in local IR galaxies. Such an interpretation is in agreement with the observation that many of the distant, cold, SMGs are extended on scales of $\sim 10$ kpc (Chapman et al. 2004) in contrast with the compact ULIRGs seen locally, and is also consistent with the change in the mean IR SED of luminous galaxies as inferred from the observed 70 $\mu$m to radio flux density ratio of high redshift star forming galaxies (Seymour et al. 2009). In addition, changes in dust properties (such as opacity, grain distribution etc.) with redshift are also a possible cause of the larger spread in SED types at high redshift.

Most galaxy evolution models (e.g. Lagache et al. 2005; Pearson 2003; Le Borgne et al. 2009; Rowan-Robinson 2009) assume that the IR SED is only dependent on IR luminosity, i.e. they typically use certain templates for star forming galaxies of a given luminosity, often using local galaxies like Arp 220 (which can be characterised as having a hot IR SED by our definition) for the most luminous population. This choice was often necessary as there were few constraints on any change with redshift until now. Models based on cooler SEDs could, for example, reconcile the flat or decreasing star formation rate density above $z = 1$ and the far-IR and sub-millimetre source counts.

In conclusion, we have found that the star formation history of the Universe is dominated by cold galaxies across $0 < z < 1$ and that the hot luminous IR galaxies we see locally are not representative of the luminous galaxies that make up the bulk of the star formation at $0.1 < z < 1$.

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REFERENCES

Alexander D. M., et al., 2003, Astron. J., 126, 539
Bunker A. J., Stanway E. R., Ellis R. S., McMahon R. G., 2004, MNRAS, 355, 374
Chapman S. C., Blain A. W., Smail I., Ivison R. J., 2005, ApJ, 622, 772
Chapman S. C., Helou G., Lewis G. F., Dale D. A., 2003, ApJ, 588, 186
Chapman S. C., Smail I., Windhorst R., Muxlow T., Ivison R. J., 2004, ApJ, 611, 732
Clements D. L., et al., 2008, MNRAS, 387, 247
Cowie L. L., Songaila A., Hu E. M., Cohen J. G., 1996, AJ, 112, 839
Davis M., et al., 2007, ApJL, 660, L1
Elbaz D., et al., 2007, A&A, 468, 33
Farrah D., et al., 2007, ApJ, 667, 149
Felten J. E., 1976, ApJ, 207, 700
Feulner G., Gabasch A., Salvato M., Drory N., Hopp U., Bender R., 2005, ApJL, 633, L9
Gehrels N., 1986, ApJ, 303, 336
Hopkins A. M., Beacom J. F., 2006, ApJ, 651, 142
Huynh M. T., Frayer D. T., Mobasher B., Dickinson M., Charry R.-R., Morrison G., 2007, ApJL, 667, L9
Juneau S., et al., 2005, ApJL, 619, L135
Kennicutt Jr. R. C., 1998, ApJ, 498, 541
Lagache G., Puget J.-L., Dole H., 2005, ARA&A, 43, 727
Le Borgne D., Elbaz D., Ocvirk P., Pichon C., 2009, A&A, 504, 727
Le Floc’h E., et al., 2005, ApJ, 632, 169
Lewis I., et al., 2002, MNRAS, 334, 673
Lilly S. J., Fevre O. L., Hammer F., Crampton D., 1996, Astrophys. J., 460, L1
Lonsdale C. J., Helou G., 1987, ApJ, 314, 513
Madau P., Ferguson H. C., Dickinson M. E., Giavalisco M., Steidel C. C., Fruchter A., 1996, MNRAS, 283, 1388
Magnelli B., Elbaz D., Charry R. R., Dickinson M., Le Borgne D., Frayer D. T., Willmer C. N. A., 2009, A&A, 496, 57
Pearson C., 2005, MNRAS, 358, 1417
Rieke G. H., Alonso-Herrero A., Weiner B. J., Pérez-González P. G., Blaylock M., Donley J. L., Marcillac D., 2009, ApJ, 692, 556
Rowan-Robinson M., 2009, MNRAS, 394, 117
Sanders D. B., Mazzarella J. M., Kim D.-C., Surace J. A., Soifer B. T., 2003, AJ, 126, 1607
Sanders D. B., Mirabel I. F., 1996, Ann. Rev. Astron. Astrophys., 34, 749
Schmidt M., 1968, ApJ, 151, 393
Seymour N., et al., 2008, MNRAS, 386, 1695
Seymour N., Huynh M., Dwelly T., Symeonidis M., Hopkins A., M’Hardy I. M., Page M., Rieke G., 2009, MNRAS in press, astro-ph/0906.1817
Siebenmorgen R., Krügel E., 2007, A&A, 461, 445
Spergel D., et al., 2003, Astrophys. J., Suppl. Ser., 148, 175
Symeonidis M., et al., 2007, ApJL, 660, L73
Symeonidis M., Page M. J., Seymour N., Dwelly T., Coppin K., McHardy I., Rieke G. H., Huynh M., 2009, MNRAS, 397, 1728 (S09)

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