Submillimetre surveys: The prospects for Herschel

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Accepted 22nd June 2009.

ABSTRACT

Using the observed submillimetre source counts, from 250-1200 microns (including the most recent 250, 350 and 500 micron counts from BLAST), we present a model capable of reproducing these results, which is used as a basis to make predictions for upcoming surveys with the SPIRE instrument aboard the Herschel Space Observatory. The model successfully fits both the integral and differential source counts of submillimetre galaxies in all wavebands, predicting that while ultra-luminous infrared galaxies dominate at the brightest flux densities, the bulk of the infrared background is due to the less luminous infrared galaxy population. The model also predicts confusion limits and contributions to the cosmic infrared background that are consistent with the BLAST results. Applying this to SPIRE gives predicted source confusion limits of 19.4, 20.5 and 16.1 mJy in the 250, 350 and 500 micron bands respectively. This means the SPIRE surveys should achieve sensitivities 1.5 times deeper than BLAST, revealing a fainter population of infrared-luminous galaxies, and detecting approximately 2600, 1300, and 700 sources per square degree in the SPIRE bands (with one in three sources expected to be a high redshift ultra-luminous source at 500 microns). The model number redshift distributions predict a bimodal distribution of local quiescent galaxies and a high redshift peak corresponding to strongly evolving star-forming galaxies. It suggests the very deepest surveys with Herschel-SPIRE ought to sample the source population responsible for the bulk of the infrared background.

Key words: Cosmology: source counts – Galaxies: surveys, evolution.

1 INTRODUCTION

Over two decades ago, a large number of galaxies that emit the bulk of their luminosity in the restframe far-IR were detected in the IRAS All-Sky Survey (typically at $z < 0.1$). These so-called luminous and ultra-luminous infrared galaxies (LIRGs $10^{11}L_\odot < L_{\text{IR}}(8-1000\mu m) < 10^{12}L_\odot$ and ULIRGs $L_{\text{IR}} > 10^{12}L_\odot$) are powered by a combination of star formation and active galactic nucleus (Soifer et al. 1987), but only recently have they been shown to be an important population in the early Universe. This is in part due to the achievements of submillimetre continuum observations using ground-based facilities: pioneering surveys at 850μm with SCUBA on the JCMT begat the discovery of submillimetre galaxies (SMGs; e.g., Smail, Ivison & Blain 1997, Barger et al. 1998, Hughes et al. 1998, Eales et al. 1999) which were subsequently constrained to be mainly distant star-forming galaxies (e.g., Chapman et al. 2003). These characteristics were shared with SMGs found in other submillimetre bands e.g., 1100μm (Laurent et al. 2005, Bertoldi et al. 2000) and 350μm (Khan et al. 2007). Larger surveys (e.g. the SCUBA SHADES survey, Mortier et al. 2005) have confirmed these sources are strongly evolving (Coppin et al. 2008). However, the discovery of SMGs still poses challenges to semi-analytical hierarchical models of galaxy formation (e.g. Guiderdoni et al. 1998, Ballard et al. 2003), and questions remain over their role in the formation of elliptical galaxies and supermassive black holes (Magorrian et al. 1998) and the energy budget between star-formation and accretion in the Universe.

In this work we present a galaxy evolution model that successfully reproduces the source counts from 250-1200μm,
including both the large area SCUBA surveys and the latest results from the BLAST telescope (Pascale et al. 2008). In Section 2 we describe the model and present fits to the galaxy counts in Section 3. The launch of SPIRE on-board the Herschel Space Observatory offers an opportunity to examine an SMG population that overlaps with ground-based observations and IR-luminous galaxies selected at mid – far-IR wavelengths (e.g., with IRAS, AKARI, Spitzer). SPIRE will perform surveys at 250, 350, 500µm and in Section 4 we discuss the prospects for upcoming surveys with Herschel. Throughout this work a concordance cosmology of $H_0 = 72 \text{km} \text{s}^{-1} \text{Mpc}^{-1}$, $\Omega = 0.3$, $\Lambda = 0.7$ is assumed.

2 THE GALAXY EVOLUTION MODEL

To model the submillimetre source counts we use a far-IR backward evolution framework following the models of Pearson (2005), Pearson et al. (2007). These models were previously successfully used to reproduce the combined mid-infrared source counts from ISO & Spitzer at 15µm & 24µm. These models have now been updated to produce source counts from 1-1000µm and will be reported in detail in Pearson (2009). Although submillimetre luminosity functions are available (e.g. Serjeant & Harrison 2003), to model the counts we retain the 60µm luminosity function derived from the IRAS Point Source Catalogue (Saunders et al. 2000) since it is defined around the peak of the dust emission and contains a large ensemble of sources segregated by population class. The source counts are fit to the wavelength where the luminosity function is defined, $\lambda_{LF}$, which sets the baseline normalization of all parameters. To predict the counts at other wavelengths, the luminosity function is shifted to the observation wavelength, $\lambda_{obs}$, using the ratio $L(\lambda_{obs})/L(\lambda_{LF})$, obtained via model template spectra, no other priori is assumed. Spectral templates are drawn from four source populations, comprising normal quiescent galaxies and three star-forming groups consisting of, with increasing luminosity, starburst galaxies, LIRGs and ULIRGs (modelled on the archetype Arp220). An additional AGN component (based on the emission from a dust torus) is also included within the model framework of Pearson (2009), however it is found that AGN do not contribute significantly to the source counts in the submillimetre and although included, their contribution is not considered in this work. The normal galaxy spectral templates are from the libraries described in Efstathiou & Rowan-Robinson (2003) which exhibit cool far-IR/submillimetre colours, with spectra peaking between 100-200µm. The adopted starburst, LIRG & ULIRG spectral templates are taken from the spectral models of Efstathiou et al. (2000), which provide good fits to the IRAS, ISO and Spitzer galaxy populations (Rowan-Robinson et al. 2004, Rowan-Robinson et al. 2005). Note that all templates are independent of the observed data sets being fitted.

Follow-up SCUBA imaging of local IRAS-selected galaxies has implied colder far-IR/submillimetre colours in SMGs than those derived from galaxy spectra based purely on IRAS colours (Dunne et al. 2006, Vlahakis et al. 2005). The colours of our model templates agree with this, as they follow the trend of the local galaxy colours extremely well in Figure 1. Although deeper SCUBA surveys are expected to principally select LIRG/ULIRGs (Blain et al. 2002), this local sample also comprises lower luminosity starburst and cooler normal galaxies (also predicted to contribute at higher redshifts Efstathiou & Rowan-Robinson 2003).

The star-forming populations follow the burst evolution-ary scenario of Pearson (2003, Pearson (2009), modelled by an exponential function to $z \sim 1$ and a power-law thereafter. This evolution is consistent with a rapid onset of star-formation at high redshift, a gradual decline to redshift of $\sim 1$ and a sharp decline in activity to the present epoch. The relative contribution of each component to the overall star-formation rate follows a downsizing pattern with redshift in which the most massive galaxies formed stars at an early epoch, thus dominating the star-formation history in the early Universe (e.g. Mobasher et al. 2009).

3 SOURCE COUNTS AND RESULTS

The model fits to the observed source counts at 250, 350, 500, 850 and 1100µm are shown in Figure 2 with the total model source counts shown alongside the respective contributions of the assumed galactic populations (normal and starburst galaxies, LIRGs and ULIRGs).

Figure 2 panels a, c & d show the model fits to the differential counts (normalised to a Euclidean universe) from the Balloon-borne Large-Aperture Submillimeter Telescope (BLAST, Pascale et al. 2008) survey in the GOODS field (Devlin et al. 2009), for the 250, 350 & 500µm bands respectively. In all the BLAST bands, it is predicted that the brightest counts (>1 Jy in the non-evolving Euclidean regime of the counts) will be dominated by quiescent normal galaxies, expected to be bright, local galaxies at redshifts <0.5 (see Figure 3). Here the model predicts 2.7 sources at 250 µm over the BLAST survey area of 8.7 deg², compared with the three sources found in the brightest bin of the source list of Devlin et al. 2009. The steep departure from Euclidean counts is caused by the ULIRGs but
at the peak of the differential source counts the less luminous LIRGs are the dominant population. At 250 µm, the model slightly over-predicts the source counts at >60 mJy, but this is within the BLAST error bars. There is a sharp rise in the counts at the 200 mJy level, and a turn-over between 100 and 20 mJy (although the BLAST counts in this region may be less reliable as the instrument is confusion-limited), with the model predicting a second turn-over at <10 mJy. Due to the strong negative K-corrections in the submillimetre (Franceschini et al. 1994), the flux densities of distant galaxies are enhanced such that the luminosity function at lower luminosities is sampled at fainter flux densities, with any break in the counts being attributed to a change in the dominant population. The BLAST counts are derived from a P(D) analysis rather than source catalogues and provide a statistical constraint on the slope of the source counts at faint fluxes which are already source confused. Encouragingly at 350 µm, the faintest BLAST counts are consistent with the differential counts from the deeper (non-confused) 350 µm survey using SHARC II in the Bootes field by Khan et al. (2007). Figure 2 shows the 350 µm integral source counts from same survey and the SCUBA 450 µm counts (Smail et al. 2002 assuming an Arp 220 spectral template to transform the counts to this band). The model fits these observations well, predicting breaks in the source counts at ∼10 and ∼10 mJy, and that the deeper SHARC II results are dominated by LIRGs. In the 500 µm BLAST band, the model fit is exceptionally good, from the steep rise from Euclidean values at S < 300 mJy, to the turn-over between 30-6 mJy. The model predicts turnovers in the counts at fainter flux densities of 10, 8, 5 mJy in the 250, 350 & 500 µm bands, all within the constraints imposed by equating the integrated surface brightness of the BLAST sources to the emission from the infrared background derived from a power-law extrapolation and naive cut-off of sources estimated by Devlin et al. (2004) to be 7.0±1.3, 7.2±1.7 & 4.6±1.2 mJy at 250, 350 & 500 µm respectively.

At longer submillimetre wavelengths, the model fits are compared with the observed integral source counts from the myriad surveys carried out with SCUBA at 850 µm (Figure 3). These observations span two orders of magnitude in flux density and thus provide the best pre-Herschel constraints on the galaxy counts. The models provide a good fit to the counts from the brightest flux densities down to 0.5 mJy below the SCUBA-850 µm confusion limit of 2 mJy (from the lensed surveys of Smail, Ivison & Blain 1997, Smail et al. 2002). At these levels, due to the strong negative K-corrections, we expect to be able to observe relatively moderate starburst galaxies. At brighter flux densities, ~10 mJy, ULIRGs are the dominant population (although a significant increasing contribution from normal galaxies cannot be
ruled out (Efstathiou & Rowan-Robinson [2003], but from the model they are predicted to dominate at $>\sim$50 mJy). The largest 850 µm survey to-date (the $\sim$0.25 deg$^2$ SHADES survey [Mortier et al. 2007]) detected 120 sources, effectively doubling the number of known SMGs. The SHADES differential source counts (Coppin et al. 2006) are shown in Figure 2(f). The best-fitting model requires a break at $\sim$4-6 mJy and it is difficult to simultaneously reconcile this with the bright-end counts, using even the most recent evolutionary models (e.g. [Rowan-Robinson et al. 2004]). However our model fits both the bright-end counts and this break due to the inclusion of the intermediate LIRG population, which are often omitted in contemporary source count models, between the starburst and ULIRG populations. The break is predicted to be due to the emergence of these strongly evolving galaxies, with their contribution peaking at $\sim$2 mJy in the differential counts.

In Figure 2, the integral source counts at millimetre wavelengths for the surveys with the BOLOCAM instrument at 1100 µm (from the maximum likelihood analysis of [Laurent et al. 2003]) and the MAMBO instrument at 1200 µm (normalising the counts to 1100 µm). BOLOCAM, MAMBO & SCUBA have all surveyed the same area – the Lockman Hole – and in essence, the counts suggest the millimetre observatories are sampling the same brighter portion (S$\alpha_{50}$ $>\sim$8 mJy) of the SCUBA 850 µm population, expected to be dominated by ULIRGs or even HLIRGs (Hyper Luminous Infra-Red Galaxies, LIR $>\sim$$10^{13}$ L$_{\odot}$). This is simply due to the longer wavelengths sampling further down the Rayleigh-Jeans slope and therefore preferentially selecting the higher luminosity, high redshift objects. Finally, the model fits to the differential counts from the recent AzTEC observations of Perera [2008] in the GOODS fields are presented in Figure 2. There is a good fit to these observed counts, with the higher luminosity sources providing the main population. The flattening seen in both the integral and differential source counts at fluxes of $\sim$3 mJy is also reproduced by the model, representing a shift in the dominant population from ULIRGs to LIRGs, with the expectation of further flattening below $\sim$1 mJy.

4 THE PROSPECTS FOR HERSCHEL

The Herschel Space Observatory [Pilbratt 2008], launched on 14th May 2009, is ESA’s next generation infrared mission. The Spectral and Photometric Imaging Receiver (SPIRE) instrument is one of the focal plane instruments and is designed for photometry and spectroscopy between 200-550 µm (Griffin et al. 2008). The three SPIRE bolometer arrays (PSW, PMW and PLW, respectively centered on 250, 350 & 500 µm, $\lambda/\Delta \lambda$ $\sim$3, with 139, 88, and 43 pixels) allow simultaneous observations over a FOV of 4'x8' in the three bands. In SPIRE’s large map scanning mode the 5σ, 1 hour point source sensitivities are expected to be 3.7, 5.3 & 4.6 mJy for the respective arrays. Despite being near identical to the three arrays on BLAST, the 3.5 m Herschel primary mirror (2m on BLAST) offers superior resolution.

The ultimate sensitivity of any survey will be the confusion limit, defined as the threshold of fluctuations in the background sky brightness caused by (unresolved) point sources below which sources cannot be discretely detected in the telescope beam $\lambda/D$, where D is the telescope diameter. The confusion due to faint galaxies is more severe at longer wavelengths and smaller apertures and is often characterized by the number of beams per source, with classical limits of 20-40 beams per source often adopted (Hoog [2001], Jeong et al. 2006). The confusion limits for Herschel-SPIRE and BLAST can therefore be compared using the source count model: for BLAST the 20 beams per source confusion limit is predicted to be 33.7, 33.6 & 23.9 mJy in the 250, 350 & 500 µm bands – agreeing very well with the estimates from Devlin et al. [2009] of 33$\pm$4, 30$\pm$7 & 27$\pm$4 mJy (implying that the faintest counts reported by BLAST are already source confused). For SPIRE, given the larger aperture, our models predict 20 beams per source confusion limits of 19.4, 20.5 & 16.1 mJy in the 250, 350 & 500 µm bands – reducing the expectation of future confusion below $\sim$1 mJy.

Figure 3. The number redshift distribution for SPIRE bands at the confusion limit of 19.4, 20.5 & 16.1 mJy for the PSW 250, PMW 350 & PLW 500µm arrays. Redshift bin size is $\Delta z = 0.1$.
of SMGs, taking submillimetre astronomy from the pioneering era into one which detailed constraints can be placed on the evolution of star-formation in the early Universe.

5 ACKNOWLEDGEMENTS

We thank Steve Willner for helpful comments and Andreas Efstathiou for providing his galaxy templates. We thank the referee for constructive comments that improved this work.

REFERENCES

Ballard C., Devriendt J.E.G., Silk J., 2003, MNRAS, 343, 107
Barger A.J.et al., 1998, Nature, 394, 248
Bertoldi F., et al., 2000, A&A, 360, 92
Blain A., Kneib J.P., Ivison R.J., Smail I., 1999, ApJ, 512, 87
Blain A., Smail I., Ivison R.J., Kneib J.-P., Frayer D.T., 2002, Physics Reports, 369, 111
Chapman S.C., Blain A.W., Ivison R.J., Smail I.R., 2003, Nature, 422, 695
Coppin K. et al., 2006, MNRAS, 372, 162
Cowie L.L.; Barger A.J., Kneib J.-P., 2002, ApJ, 603, 69
Devlin M. et al., 2009, Nature, 458, 737
Dunne L., Eales S., Edmunds M.G., Ivison R., Alexander P., Clements D. L., 2000, MNRAS, 315, 115
Eales S. et al., 1999, ApJ, 515, 518
Efstathiou A., Rowan-Robinson M., Siebenmorgen R., 2000, MNRAS, 313, 734
Efstathiou A., Rowan-Robinson M., 2003, MNRAS, 343, 322
Fixsen, D.J., Dunkley, E., Mather, J.C., Bennett, C.L., Shafer, R.A., 1998, ApJ, 508, 123
Franceschini A., Toffolatti L., Mazzèi P., Danese L., De Zotti G., 1991, AAS 89, 285
Guiderdoni, B., Hivon, E., Bouchet, F.R., Maffei, B., 1998, MNRAS, 295, 877
Greve T.R., Ivison R.J., Bertoldi F., Stevens J.A., Dunlop J.S., Lutz D., Carilli, C.L., 2004, MNRAS, 354, 779
Griffin M. et al., 2008, Proc. SPIE 7010, 701006
Hogg D., 2001, AJ, 121, 1207
Holland W. et al., 2006, Proc. SPIE 6275, 62751
Hughes D. et al., 1998, Nature, 457, 616
Jeong W-S., Pearson C.P., Lee, H.M., Pak, S-J., Nakagawa T., 2006, MNRAS, 369, 281
Khan S. et al., 2005, ApJ, 631, 9
Khan S. et al., 2007, ApJ, 665, 973
Knudsen K.K. et al., 2006, MNRAS, 368, 487
Laurent G. et al., 2005, ApJ, 623, 742
Magorrian J. et al., 1998, ArJ 115, 2295
Mobasher B. et al., 2009, ApJ, 690, 1074
Mortier A.M.J. et al., 2005, MNRAS, 363, 563
Pascale E. et al., 2008, ApJ, 681, 400
Pearson C.P. 2005, MNRAS, 358, 1417
Pearson, C.P. et al. 2007, Adv.Space Res. 40, 605
Pearson C.P. 2009, in preparation
Perera E.L., 2008, MNRAS 391, 1227
Pilbratt G.L., 2008, Proc. SPIE 7010, 701002
Rowan-Robinson M. et al., 2004, MNRAS, 351, 1290
Rowan-Robinson M. et al., 2005, ApJ, 129, 1183
Rowan-Robinson M. et al., 2009, ApJ, 394, 117
Saunders W. et al., 2000, MNRAS, 317, 55
Scott S.E. et al., 2002, MNRAS, 331, 838
Schlegel T.A., Radford S., Giovanelli R., Glenn J., Woody D., 2008, Proc. SPIE, 7012, 70121
Serjeant S., Harrison D., 2005, MNRAS, 356, 192
Small I., Ivison R.J.,Blain A.W., 1997, ApJ, 490, L5

Figure 4. CIRB fraction as a function of flux for the SPIRE/BLAST bands. solid-lines are the integral and dashed-lines are the differential contribution. Also shown are the confusion limited sensitivities for SPIRE circles and BLAST squares.

In Figure 3 we show the number redshift distribution for the three SPIRE bands at a survey sensitivity corresponding to the SPIRE confusion limit. In all bands, but most predominantly in the short wavelength 250µm band, a bimodal distribution is seen which can be interpreted as a local contribution from quiescent normal galaxies and a high redshift contribution from evolving starburst galaxies, with the high redshift peak becoming more pronounced to longer wavelengths. The median redshift of the N-z distribution lies between 2 < z < 3, consistent with the redshift distribution of SCUBA-850 500 µm arrays, with a peak at slightly brighter fluxes in all wavebands. At faint flux densities (<1mJy) 20-30% of the CIRB remains unresolved and the counts in Figure 2 indicate that the fainter starburst galaxies will become the dominant population, responsible for the remainder of the total background.

Therefore we expect the upcoming Herschel SPIRE surveys to produce the first large statistically reliable samples...
Smail I., Ivison R.J., Blain A.W., Kneib J.-P., 2002, MNRAS, 331, 495
Soifer, B.T., Neugebauer G., Houck J.R., 1987, ARAA 25, 187
Vlahakis C., Dunne L., Eales S., 2005, MNRAS, 364, 1253