An infrared–radio simulation of the extragalactic sky: from the Square Kilometre Array to Herschel

R. J. Wilman, M. J. Jarvis, T. Mauch, S. Rawlings and S. Hickey

1 Centre for Astrophysics & Supercomputing, Swinburne University of Technology, Hawthorn, Victoria 3122, Australia
2 Centre for Astrophysics, Science & Technology Research Institute, University of Hertfordshire, Hatfield AL10 9AB
3 Oxford Astrophysics, Denys Wilkinson Building, Keble Rd, Oxford OX1 3RH

Accepted 2010 February 1. Received 2010 January 25; in original form 2009 November 3

ABSTRACT
To exploit synergies between the Herschel Space Observatory and next generation radio facilities, we have extended the semi-empirical extragalactic radio continuum simulation of Wilman et al. to the mid- and far-infrared. Here, we describe the assignment of infrared spectral energy distributions (SEDs) to the star-forming galaxies and active galactic nuclei, using Spitzer 24, 70 and 160 μm and SCUBA 850 μm survey results as the main constraints.

Star-forming galaxies dominate the source counts, and a model in which their far-infrared–radio correlation and infrared SED assignment procedure are invariant with redshift underpredicts the observed 24 and 70 μm source counts. The 70 μm deficit can be eliminated if the star-forming galaxies undergo stronger luminosity evolution than originally assumed for the radio simulation, a requirement which may be partially ascribed to known non-linearity in the far-infrared–radio correlation at low luminosity if it evolves with redshift. At 24 μm, the shortfall is reduced if the star-forming galaxies develop SEDs with cooler dust and correspondingly stronger polycyclic aromatic hydrocarbon emission features with increasing redshift at a given far-infrared luminosity, but this trend may reverse at z > 1 in order not to overproduce the submillimetre source counts. The resulting model compares favourably with recent Balloon-borne Large Aperture Submillimetre Telescope (BLAST) results, and we have extended the simulation data base to aid the interpretation of Herschel surveys. Such comparisons may also facilitate further model refinement and revised predictions for the Square Kilometre Array and its precursors.

Key words: galaxies: active – galaxies: evolution – galaxies: starburst – cosmology: observations – infrared: galaxies – radio continuum: galaxies.

1 INTRODUCTION
In Wilman et al. (2008, hereafter W08), we presented a semi-empirical simulation of the extragalactic radio continuum sky primarily intended to aid the design of scientific programmes for the next generation of radio telescope facilities, culminating in the Square Kilometre Array (SKA). The simulation covers a sky area of 20 × 20 deg², and contains radio-loud and radio-quiet active galactic nuclei (AGN) and star-forming galaxies out to redshift z = 20 within a framework for their large-scale clustering. The full source catalogue – containing 320 million sources above 10 nJy at five frequencies ranging from 151 MHz to 18 GHz – can be accessed at the SKA Design Study (SKADS) Simulated Skies (S³) data base

There are by necessity numerous uncertainties and limitations in the S³–SEX simulation, including but not limited to issues such as the form of the high-redshift evolution of the AGN and galaxies, the lack of star-forming/AGN hybrid galaxies, and the abundance of highly obscured Compton-thick AGN. In so far as possible, flexibility was built into the simulations to allow post-processing to improve their accuracy as observations in the years ahead lead to improved constraints. Major advances in these areas are expected from the far-infrared (FIR) surveys to be performed by the Herschel Space Observatory (Pilbratt 2008). To facilitate such comparisons, we have post-processed the S³–SEX simulation to cover these wavelengths. In this paper, we describe the recipes for assigning infrared
spectral energy distributions (SEDs) to the radio sources, using existing mid-infrared (mid-IR) and FIR results from *Spitzer* and submillimetre survey data from SCUBA as the primary constraints. We then present our predictions for *Herschel* surveys, bolstered by a comparison with results from the Balloon-borne Large Aperture Submillimetre Telescope (BLAST) which offer a foretaste of *Herschel*’s capabilities. In keeping with the philosophy of the $S^3$ project to maximize the degree of interaction between the user and the data base, the infrared fluxes are also provided on the $S^3$ webpage from which users can generate simulation products for comparison with observations. The radio–infrared connection is of immense empirical and theoretical interest for extragalactic surveys, for the identification and follow-up of *Herschel* sources, and for probing the physics of the FIR–radio correlation and its possible evolution. The simulation can nevertheless also serves as a standalone *Herschel* simulation, for comparison with others such as the phenomenologically inspired backward evolution models of Valiante et al. (2009) and Pearson & Khan (2009), and the model of Lacey et al. (2009, hereafter L09) which is based on a semi-analytical galaxy formation model.

### 2 THE ASSIGNMENT OF INFRARED SEDS TO THE RADIO SOURCE POPULATIONS

The input radio source catalogue was obtained from the $S^3$–SEX online data base and negative evolution at high redshift was imposed using the ‘default post-processing options’ described in W08. Each radio source was assigned an infrared SED from various template libraries appropriate for star-forming galaxies and AGN, and the output flux density of each infrared model component for each galaxy [in log($F_\nu$(Jy))] was computed at observed wavelengths of 24, 70, 100, 160, 250, 350, 450, 500, 850 and 1200 μm. The wavelengths of 24, 70 and 160 μm are those of the *Spitzer* Multiband Imaging Photometer (MIPS) instrument, for which an abundance of extragalactic survey data is available to guide the construction of our model and to compare against its output (see the review of Soifer, Helou & Werner 2008). *Herschel* will conduct surveys at 250, 350 and 500 μm with the Spectral and Photometric Imaging Receiver (SPIRE) instrument and at 70, 100 and 160 μm with Photodetector Array Camera and Spectrophotometer (PACS). Longer wavelength constraints are available from submillimetre surveys by SCUBA at 450 and 850 μm, and from the Max-Planck Millimetre Bolometer (MAMBO) instrument on the 30-m Institut de Radioastronomie Millimétrique (IRAM) telescope at 1200 μm. The catalogued output flux densities are monochromatic values, with the exception of the *Spitzer* 24 and 70 μm MIPS bands for which the modelled spectra were convolved with the MIPS bandpass transmission curves, following the *Spitzer* Synthetic Photometry Recipe. This is due to the spectral complexity in the rest-frame 10 μm region, particularly for the star formation component due to the presence of polycyclic aromatic hydrocarbon (PAH) features.

The format of the output from the infrared extension, as it appears in the $S^3$–SEX online data base, is described in Appendix A.

#### 2.1 Star-forming galaxies

The population of star-forming galaxies in W08 comprises two populations, normal (or quiescent) galaxies and starbursts, identified respectively with the low- and high-luminosity Schechter function components of the local 1.4-GHz luminosity function of Yun, Reddy & Condon (2001). The entire population was evolved with pure luminosity evolution (PLE) $(1+z)^{1.1}$ out to $z = 1.5$ (defined in an Einstein–de Sitter cosmology, but adapted to the flat-$\Lambda$ cosmology used for the simulation). The default post-processing option consists of negative space density evolution of the form $(1 + z)^{-2.9}$ above $z = 4.8$. We stress that the terms ‘normal galaxy’ and ‘starburst’ are merely convenient labels for these two components of the local luminosity function in our phenomenological model. Physically speaking, the terms may not necessarily offer an accurate description of the nature of the star formation in these populations, especially beyond the local Universe.

The first step in assigning an infrared SED is to use the FIR–radio correlation for star-forming galaxies (equation 5 of Yun et al. 2001) in order to derive the rest-frame FIR luminosity, $L_{\text{FIR}}$, given the rest-frame 1.4-GHz luminosity, $L_{\nu,1.4\text{GHz}}$. The relation is characterized by the ‘q’ parameter:

$$q = \log[L_{\text{FIR}}(W)/3.75 \times 10^{12} \text{Hz}] - \log [L_{\nu,1.4\text{GHz}}(\text{WHz}^{-1})],$$

for which we assume a Gaussian distribution with $\mu = 2.34$ and $\sigma = 0.26$ (Yun, Reddy & Condon). There is evidence that this relation holds out to redshift $z > 1$ (e.g. Appleton et al. 2004; Garn et al. 2009), although such conclusions are sensitive to the assumed infrared SEDs and associated ‘k-corrections’. Indeed, using recent BLAST stacking measurements, Ivison et al. (2010) reported evidence for a tentative decline in $q_{\nu}$ (defined as the logarithmic ratio of the bolometric 8–1000 μm infrared to monochromatic 1.4 GHz radio fluxes) of the form $q_{\nu} \propto (1 + z)^{-0.14 \pm 0.03}$ (see also Kovacs et al. 2006).

The FIR luminosity, $L_{\text{FIR}}$, is traditionally defined through a linear combination of $\text{IRAS}$ 60 and 100 μm flux densities (see Sanders & Mirabel 1996), which for an SED consisting of a superposition of modified blackbodies yields the 42.5–122.5 μm luminosity to sub-per cent accuracy (Helou et al. 1988). Given $L_{\text{FIR}}$, galaxies were assigned a model SED from the library of star-forming galaxy templates assembled by Rieke et al. (2009). The latter consists of 14 SEDs uniformly spaced in total infrared luminosity (8–1000 μm), $L_{\nu,1.4\text{GHz}}$, from log $L_{\text{FIR}}(L_{\nu}) = 9.75$–13.00. The templates were taken from the online version of table 4 in Rieke et al. (2009), but they terminate on the short wavelength side at 5.26 μm for those with log $L_{\text{FIR}}(L_{\nu}) \leq 11$ and at 4.02 μm at higher luminosities. In order to predict 24 μm fluxes for galaxies at redshift $z \geq 3$, we need to extend these templates to shorter wavelengths. For this purpose, we employed the spectra of the individual local luminous infrared galaxies (LIRGs) and ultraluminous infrared galaxies (ULIRGs) in table 3 of Rieke et al. (2009), which extend down to 0.4 μm. From these, we computed mean LIRG and ULIRG spectra and matched them on to the original Rieke templates below the cut-off wavelengths of 4.02 and 5.26 μm. The ULIRG spectrum was used for the templates with log $L_{\text{FIR}}(L_{\nu}) > 12$, and the LIRG spectrum for the remaining templates. The resulting templates should be considered as schematic below ~3 μm, as we did not attempt to model the stellar population and rest-frame optical extinction in a self-consistent fashion.

The template SEDs were integrated over the appropriate wavelength ranges to yield the mapping between $L_{\text{FIR}}$ and $L_{\nu,1.4\text{GHz}}$ shown in Fig. 1; the adopted relation between the two quantities is mildly non-linear: log $L_{\text{FIR}} = 1.1 \log L_{\nu,1.4\text{GHz}} – 1.42$. Based on the IRAS Bright Galaxy Sample (Soifer et al. 1987), Marcillac et al.

---

2http://ssc.spitzer.caltech.edu/postbcd/cookbooks/synthetic_photometry.html
erg s\(^{-1}\) = −1.91 \log L_{\text{FIR}} - 1.42. The dashed line shows the linear relation \(L_{\text{FIR}} = 1.91 \, L_{\text{TIR}}\) assumed by Marcillac et al. (2006).}

At a given \(L_{\text{FIR}}\), the local galaxy population exhibits a distribution in 60–100 \(\mu\)m colour or, equivalently, dust temperature, as characterized by Chapin, Hughes & Aretxaga (2009). We use this distribution (Chapin et al. 2009, equations 8 and 9) to assign each star-forming galaxy a 60–100 \(\mu\)m colour, \(C\), defined as the ratio of the rest-frame monochromatic 60 and 100 \(\mu\)m flux densities: \(C = \log L_{60}/L_{100}\). The template nearest in colour is then selected from the Rieke library using the empirical \(C\)–\(L_{\text{TIR}}\) conversion for these templates shown in Fig. 3, for which a functional fit is

\[
C = 0.33\tanh\{1.1[\log L_{\text{TIR}} - 11.0]\} - 0.23. \tag{2}
\]

Having selected the template shape from the Rieke library by this process, the final step is to normalize it to the actual value of \(L_{\text{FIR}}\) originally specified by the FIR–radio relation. This is done using the non-linear \(L_{\text{FIR}}\)–\(L_{\text{TIR}}\) relation given in Fig. 1. Chapin et al. (2009) presented evidence for evolution in the colour–luminosity relation, but we initially assume that the local relation applies at all redshifts.

\[L_{\text{TIR}} = 44.7 + 4.62 \times 10^{-0.27(\log L_{\text{FIR}} - 4.375)g(z)}, \tag{3}\]

where \(\beta = -0.281\), and \(g(z)\) is evolution of the form \((1 + z)^{0.62}\) out to \(z = 2\) and flat thereafter. The number of Compton-thick obscured AGN is not as well constrained, and in W08 we simply boosted the space density of the Ueda et al. (2003) luminosity function by 50 per cent in a notional allowance for them, but left the issue open for subsequent refinement in post-processing. Ueda et al. showed that a reasonable match to the X-ray background results if the number of Compton-thick AGN simply equals the number of Compton-thick obscured AGN. We thus assume that the abundance of Compton-thick AGN population is a factor of \(f_{\text{chk}}\) times that of the combined population of unobscured and Compton-thick obscured AGN, where \(f_{\text{chk}} = \min[0.5, f_2]\), with the upper bound of 0.50 hard-wired into the W08 simulation. After the removal of any excess Compton-thick AGN, the remaining sources in the W08 catalogue are probabilistically identified as unobscured (type I), Compton-thin or Compton-thick obscured (type II) AGN. Finally, 10 per cent of all sources are flagged for removal because W08 included radio-loud AGN with a separate radio luminosity function, but this population is also implicitly present in the Ueda et al. luminosity function. The fractions of retained radio-quiet AGN which are unobscured, Compton-thin and Compton-thick obscured are shown as functions of \(L_X\) and redshift in Fig. 4.

\[f_2 = [0.27 + \beta(\log L_X - 43.75)]g(z),\]

\[X = 2.2 \text{ Radio-quiet AGN}\]

In W08, a population of radio-quiet AGN was incorporated using the Ueda et al. (2003) hard X-ray luminosity function and a relation between 2–10 keV and 1.4 GHz luminosities. To assign infrared SEDs the first task is to split the population into subgroups of unobscured AGN, and Compton-thin and Compton-thick obscured AGN. This was not done in W08 but is now necessary because the infrared SEDs are sensitive to this classification. We start from the findings of Hasinger (2008), who used a compilation of hard X-ray surveys to parametrize the fraction of obscured Compton-thin AGN (as a proportion of a total population comprising unobscured AGN and obscured Compton-thin AGN, but excluding Compton-thick obscured AGN) as a function of \(L_X\) (2–10 keV luminosity; erg s\(^{-1}\)),

\[f_2 = \frac{L_X^{2.2}}{L_{\text{FIR}}}, \tag{2}\]

where \(L_X\) is inferred from the radio luminosity using equation (2) of W08. Sources with \(L_X\) above and below a threshold of \(3 \times 10^{44}\) erg s\(^{-1}\) are classified as quasars and Seyferts, respectively. Unobscured (type I) quasars are assigned
at random one of the three templates for optically selected quasi-stellar objects (QSOs) compiled by Polletta et al. (2007) (termed QSO1, BQSO1 and TQSO1, which differ in their relative optical/infrared flux ratios). The unobscured Seyferts are assigned SEDs from the online library of models computed by Nenkova et al. (2008) using the CLUMPY code for dust radiative transfer in a clumpy AGN torus. To narrow down the parameter space of available models, we use the results of Thompson et al. (2009) which are based on analysis of Seyfert 1 AGN mid-IR spectra. They prefer a range of CLUMPY parameter space defined by the parameters $Y = 30$, $q = 1$, $\sigma = 45^\circ$, $m = 2$, $i = 30^\circ$, $\tau_V = 30 - 60$ and $N_0 \leq 6$ (see Nenkova et al. 2008 for the meaning of these parameters). 18 CLUMPY models satisfy these constraints and were assigned at random to our type I Seyferts, with the SED consisting of the reprocessed torus emission and direct AGN broken power-law emission (defined as a power-law $F_\lambda \propto \lambda^{-1.5}$ over 0.1–1 $\mu$m with a Rayleigh–Jeans slope at longer wavelengths).

For the type II Compton-thin AGN, we assigned one of the type 2 QSO templates given by Polletta et al. (2006) and Polletta et al. (2007) (termed QSO2 and Torus, respectively) for the quasars, and one of the aforementioned CLUMPY models (but without the direct AGN emission component) to the Seyferts.

For the Compton-thick AGN, we assigned half the population SEDs using the same prescription as for the type II Compton-thin sources; for the other half of the population, we reflect the growing body of evidence which suggests that a large proportion of Compton-thick AGN are obscured by an extended distribution of cold dust in the host galaxy and not by a nuclear torus (see e.g. Polletta et al. 2006, 2008; Martínez-Sansigre et al. 2006; Lacy et al. 2007). Accordingly we assign these sources an intrinsic type I or Compton-thin type II SED, extinguished by a dust screen with $A_V = 4$–27 mag (as found by Polletta et al. 2008 for obscured quasars). An extinction curve extending into the infrared is taken from McClure (2009). These AGN infrared SED components are normalized using the correlation between 12 $\mu$m and hard X-ray emission found by Gandhi et al. (2009), which appears to hold for obscured and unobscured AGN (including Compton-thick sources) and to extend into the quasar regime,

$$\log L_{\text{MIR}} = (-4.37 \pm 3.08) + (1.06 \pm 0.071) \log L_X, \quad (4)$$

where $L_{\text{MIR}} = \lambda L_\lambda$ at 12.3 $\mu$m in erg $s^{-1}$. Gaussian scatter of $\sigma = 0.36$ is assumed on the relation.

2.2.2 Star formation

There is abundant evidence for ongoing star formation in the host galaxies of radio-quiet AGN and this is likely to dominate the FIR SED. The consensus emerging from targeted observations of local Seyferts (Buchanan et al. 2006; Thompson et al. 2009) and studies of more distant samples and cosmological surveys (e.g. Hernández-Caballero et al. 2009; Serjeant & Hatziminaoglou 2009; Silverman et al. 2009) is that the star formation is generally higher in obscured AGN compared with their unobscured counterparts, and increases sublinearly with AGN luminosity. We embody these findings with
and this is used to normalize the SED. For simplicity, we assume the same (local) relation between $K$-band luminosity and radio power at all redshifts. An artefact of this choice of model is that the mid-IR and FIR regions of the SED template increase sharply for ages below the assumed duration of the starburst (1 Gyr). This causes discontinuities in the mid-IR and FIR fluxes at $z \approx 4$ where the galaxy age first drops below this figure.

### 2.3.2 FRIs

The FRIs are first split into populations of quasars and radio galaxies for which the nuclear emission is seen directly and through obscuration, respectively. Willott et al. (2000) found that for log $L_{151\text{ MHz}}[W\text{ Hz}^{-1}\text{ sr}^{-1}] > 26.5$, the quasar fraction is 0.4, independent of redshift and luminosity, and around 0.1 at lower radio luminosity. Taking into account the contamination by FRIs at lower luminosity, we simply assume that 40 per cent of our FRIs are seen as quasars, i.e. those seen at viewing angle of $\leq 53^\circ$ to the jet axis. To assign AGN and starburst infrared SEDs, we recall that quasars are, on average, more intrinsically luminous AGN than the radio galaxies (see e.g. Simpson 2003). To work with a parameter that is closely tied to the intrinsic strength of the nuclear emission, we convert from $L_{151\text{ MHz}}[W\text{ Hz}^{-1}\text{ sr}^{-1}]$ to $L_{[\text{O}\text{III}]}\lambda5007[W]$ using a relation from Grimes, Rawlings & Willott (2004),

$$log L_{[\text{O}\text{III}]}\lambda5007 = 7.53 + 1.045 \log L_{151\text{ MHz}}.$$  

Equation (6) applies to the population as a whole, but following Grimes et al. (2004) we assume that the quasars and radio galaxies lie 0.3 dex systematically above and below it, respectively, with an additional 0.5 dex of scatter on each distribution. To assign an AGN component to the infrared SED, we draw upon the findings of Haas et al. (2008) who presented Spitzer 3–24 μm photometry of Third Cambridge Catalogue of Radio Sources (3CR) steep-spectrum quasars and radio galaxies at redshift $1 < z < 2.5$. The quasar mid-IR SEDs are very uniform, roughly constant in $\nu F_{\nu}$. There is a near proportionality between $\nu F_{\nu}$ and $\nu F_{\nu},(178\text{ MHz},\text{ rest})$ with 0.5 dex scatter. The radio galaxies are dominated by host galaxy starlight below 3 μm (rest) and at longer wavelengths by a quasar nucleus reddened by up to $A_V = 50$ mag. The radio galaxies are a factor of 3–10 less luminous in this spectral range than the quasars, which they attribute entirely to extinction. For a sample of 3CR sources at $0.4 \leq z < 1.2$, Cleary et al. (2007) find that the quasars are 4 times as luminous as the radio galaxies at 15 μm, half of which they attribute to extinction, and half to synchrotron contamination in the quasars. However, their sample includes a significant number of steep-spectrum compact and superluminal quasars. They also assumed a spherically symmetric dust model, which is likely to be inadequate.

We assume that the quasars and radio galaxies follow the same intrinsic relation between $\nu L_{\nu}(8\text{ μm},\text{ rest}) [W]$ and $L_{[\text{O}\text{III}]}\lambda5007 [W]$, derived from the quasar points in fig. 1 of Haas et al. (2008) using equation (6) to convert from $L_{151\text{ MHz}}$ to $L_{[\text{O}\text{III}]}\lambda5007$.

We assume

$$log \nu L_{\nu}(8\text{ μm, rest}) = 3.3 + 0.9569 \log L_{[\text{O}\text{III}]}\lambda5007.$$  

No intrinsic scatter is assumed on this, as the scatter in equation (6) can reproduce the scatter in fig. 1 of Haas et al. (2008). Using this normalization, we assign the quasars randomly to one of the three type I quasar templates from Polletta et al. (2007). The radio galaxies are also assigned one of these template SEDs in an analogous manner, and then extinction of $A_V = 0–40$ mag is applied. An elliptical host galaxy model from the GRASIL library

$\text{SFR} = 0.63 \sqrt{L_X/10^{43}}(1 + z)^{1.6} M_\odot\text{ yr}^{-1}.$  

(5)

For the type II AGN (Compton-thin and Compton-thick), we base our results on the $z = 0.1$ SDSS type II AGN sample of Kauffmann et al. (2003), focussing on the subsample of luminous sources with log $L(\text{[O}\text{III}]) > 40.5$ indicated by the red dots in fig. 10 of Silverman et al. (2009). Referring once more to the log $L(\text{[O}\text{III}])$ distributions in fig. 4(b) of Kim et al. (2006), we infer for this particular luminosity-limited sample a median log $L(\text{[O}\text{III}])=41.1$, which translates into log $L_X = 42.25$ and hence boosts the prefactor of our assumed SFR($L_{X,z}$) relation from 0.63 to 2 $M_\odot\text{ yr}^{-1}$. A scatter of 1 dex is assumed on the SFR($L_X$, $z$) relation and the star-formation rates are assumed to decline as $(1 + z)^{-0.9}$ at $z > 4.8$ following the assumed evolution of the global SFR density. SEDs for the star formation component are assigned from the Rieke et al. (2009) library, using the relation given by Yun et al. (2001) (their equation 13) to relate the SFR and 1.4-GHz radio luminosity; the FIR–radio relation (equation 1) was then used to assign $L_{\text{FIR}}$ and hence an appropriate template from the Rieke library using Fig. 1.

### 2.3 Radio-loud AGN

Radio-loud AGN were modelled by W08 using the Willott et al. (2001) 151-MHz luminosity function comprising a weakly evolving low-luminosity component and a rapidly evolving high-luminosity component, identified with Fanaroff–Riley type I (FRI) and FRII radio sources, respectively. We consider them separately for the purposes of infrared SED assignment.

#### 2.3.1 FRIs

There is scant evidence for the presence of intrinsically luminous optical–ultraviolet AGN in the radio population we associate with FRI sources (e.g. Vardoulaki et al. 2008). We therefore model their infrared SEDs with a template representing host galaxy starlight only, which we produced using the GALSYNTH online interface to the GRASIL code developed by Silva et al. (1998). The models are based on their ‘Elliptical model’, which gives the evolving SED (taking account of dust reprocessing) of a stellar population formed in a burst of 1 Gyr duration (see description of this particular model at http://adlibitum.oat.ts.astro.it/silva/grasil/modlib/modlib.html). We generated models with ages separated by 0.1 Gyr for 0.1–1.5 Gyr, and by 1 Gyr for ages 2–13 Gyr. We assume formation redshifts distributed uniformly in the range $z = 10–20$, and select the template nearest in age at the redshift of the galaxy under consideration. To normalize the SEDs, we draw upon the bivariate 1400 MHz–$K$-band luminosity function derived by Mauch & Sadler (2007) for a local sample: given a radio power, the absolute $K$-band magnitude is drawn from a Gaussian distribution of specified mean and variance.
is assigned for the FRIs, but in this case normalized using the $K$–z relation of Willott et al. (2003) with an additional offset of $\Delta K = -0.36(\log L(151 \text{ MHz})[\text{ W Hz}^{-1}\text{ sr}^{-1}]) - 26.55$ mag (following Willott et al. 2003, Fig. 3).

In principle, the evolving elliptical template from the grasil library should self-consistently reproduce the FIR dust emission. To compare with this, we included in addition a FIR dust component to explicitly match the starburst properties to the submillimetre observations of radio galaxies and quasars by Archibald et al. (2001), Willott et al. (2002) and Reuland et al. (2004). From Willott et al. (2002), the radio quasars appear to be a factor of several brighter than the radio galaxies at 850 $\mu$m. In Grimes, Rawlings & Willott (2005), this was enshrined as a universal relationship between $L([\text{O} \text{III}]\lambda5007) [\text{ W}]$ and $L(850 \mu\text{m}) [\text{ W Hz}^{-1}\text{ sr}^{-1}]$,

$$\log L(850 \mu\text{m}) = -2.5753 + 0.682 \log L([\text{O} \text{III}]\lambda5007),$$  

with additional scatter drawn from a Gaussian of $\sigma = 0.44$. With this normalization, we adopt a modified blackbody with $\beta = 1.95$, $T = 41 \text{ K}$, as found by Priddey & McMahon (2001) for high-redshift quasars. Archibald et al. (2001) found $L(850 \mu\text{m}, \text{rest})$ to be a strongly increasing function of redshift, but for our adopted SED parameters, the redshift dependence is a more modest $(1 + z)^{1.5}$ (see Reuland et al., Fig. 4); this dependence is added to equation (8) and normalized at $z > 2.5$. There is evidence for a decline in $L(850 \mu\text{m}, \text{rest})$ at $z > 4$, so in common with other parts of the simulation we assume a decline of the form $(1 + z)^{-7.9}$ at $z > 4.8$. We note, however, that Rawlings et al. (2004) found any explicit redshift dependence to be small or absent. Although Willott et al. (2002) found tentative evidence for an anticorrelation between radio-source size and submillimetre luminosity for quasars, no such trend was found for the radio galaxy sample of Reuland et al. (2004), and we have chosen not to incorporate one.

Finally, we remark that our treatment of the infrared SED is confined to reprocessed dust emission due to star formation and AGN heating. As a result, we have not endeavoured to incorporate an infrared synchrotron emission component in the beamed radio-loud AGN. If required, such a component could be added as an extrapolation of the radio SED given in the $S^3$ data base, following the beaming treatment described by W08. It would only have a significant effect on the predicted source counts at the brightest flux densities.

### 3 COMPARISON WITH EXISTING OBSERVATIONS

The prescriptions outlined in Section 2 constitute our ‘baseline model’. Here, we compare its source counts and other derived quantities against observations. In Fig. 5, we show the normalized differential source counts at 24, 70 and 160 $\mu\text{m}$ for comparison with the most recent Spitzer MIPS survey results. To generate these plots, we used a 4-deg$^2$ area of the input radio simulation, coupled with a shallow subset of the full 400-deg$^2$ radio simulation area to generate the bright flux ends (above 1.6 mJy at 24 $\mu\text{m}$, 30 mJy at 70 $\mu\text{m}$ and 100 mJy at 160 $\mu\text{m}$). The simulated counts fall decisively short of
4 REVISIONS TO THE BASELINE MODEL

We now adapt the baseline model to provide a better match to the existing infrared source count data. We focus entirely on the star-forming galaxies and perform modifications in two steps, motivated by recent observational findings. First, we use post-processing to modify the cosmological luminosity evolution of the star-forming galaxies to remove the shortfall in the 70 μm source counts. Secondly, we allow the SED template assignment procedure to evolve towards cooler templates at higher redshift in an attempt to rectify the deficit in the 24 μm counts.

4.1 Modifications to the luminosity evolution of the star-forming galaxies

In W08, we assumed that the radio luminosity function of the star-forming galaxy population undergoes PLE of the form \((1 + z)^p\) with \(p = 3.1\) out to \(z = 1.5\), applied in an Einstein–de Sitter cosmology, but adapted to the flat \(\Lambda\) cosmology of the simulation. Since then, new observational constraints on the evolutionary form have been published. At 70 μm, Huynh et al. (2007) constrained the evolution out to \(z \sim 1\) and found a degeneracy between luminosity and density evolution with \(p = 2.78\) in the PLE case; using several Spitzer surveys, Magnelli et al. (2009) found redshift evolution consistent with PLE with \(p = 3.6 \pm 0.4\) out to \(z \sim 1.3\). Both these studies derived the evolution for a flat \(\Lambda\) cosmology, which for a given functional form of PLE leads to a higher abundance of galaxies than present in the W08 simulation. The discrepancy is especially pronounced at and below the break in the luminosity function. We can, however, correct for it by boosting the luminosity of the star-forming galaxies in the W08 catalogue by an amount \(\Delta \log L(L, z)\). The boost required to bring the W08 luminosity function into agreement with PLE of \(p = 3.1\) to \(z = 1.5\) in a \(\Lambda\) universe is shown in Fig. 8. [We note, however, that the local luminosity function is flat below 20.6 W Hz\(^{-1}\), in which regime no luminosity boost can compensate for the deficit in space density;
Figure 8. The boost in luminosity, $\Delta \log L(L, z)$ (dex), which must be applied to the star-forming galaxies in the W08 catalogue to transform to PLE of the form $(1 + z)^{3.1}$ to $z = 1.5$ in a $\Lambda$-Universe. The lines show redshifts $z = 0.08$ (solid), 0.45 (short dashed), 0.83 (dotted), 1.2 (dot–dashed) and 1.5 (long dashed).

Figure 9. 24, 70 and 160 $\mu$m source counts for the modified model of Section 4.1, in which the luminosity of the star-forming galaxies is boosted to mimic PLE in a $\Lambda$-universe. Symbols and observed data are as in Fig. 5.

4.2 Evolution towards cooler dust templates and the final model

There is growing evidence that the one-to-one correspondence between infrared luminosity and template SED established in the local Universe breaks down at earlier cosmic epochs. To cite several examples, Symeonidis et al. (2009) showed that luminous and ultraluminous galaxies out to redshift $z \sim 1$ have much cooler dust distributions (i.e. SEDs peaking at longer wavelengths) than their local counterparts in the IRAS Bright Galaxy Sample (see also Symeonidis et al. 2008); and in the mid-IR, Farrah et al. (2008) showed that ULIRGs at $z \sim 1.7$ have spectral features characteristic of starbursts with luminosities $10^{10} - 11 L_\odot$, rather than local ULIRGs. Such trends may reflect more spatially extended star-forming regions at higher redshifts with lower dust optical depths. Based on a study of submillimetre galaxies at $z \sim 2.5$, Chapin et al. (2009) argued for luminosity evolution in the colour–luminosity relation of the form $(1 + z)^3$, in the sense that the SED becomes cooler at higher redshift (see also Pope et al. 2006).

Building on these findings, we now introduce phenomenological modifications to the SED template assignment procedure with the aim of reducing the remaining deficit in the 24 $\mu$m source counts (Fig. 9). With reference to the Rieke templates in Fig. 2, we see that for a given $L(FIR)$, evolution towards cooler dust templates with increasing redshift can significantly boost the observed 24 $\mu$m flux relative to that at 70 $\mu$m. Accordingly, the $L(FIR)$ is scaled down by a factor of $f(z)$ for the purposes of selecting the FIR colour, $C$, from the $C–L(FIR)$ distribution (see Section 2.1). The chosen template is, however, still normalized to the original value of $L(FIR)$.
After some experimentation, we chose a function which evolves as \( f(z) = (1 + z)^{-5} \) out to \( z = 1 \). Beyond \( z \sim 1 \), the evolution towards cooler templates must stop or go into reverse in order not to overproduce the 850 \( \mu m \) counts. We chose a decline of the form \( (1 + z)^{-1.5} \) from \( z = 1 \) to 2, flat thereafter. Even with this in place, the starbursts still overproduce the bright end of the 850 \( \mu m \) source counts above 10 mJy if we retain the ‘default post-processing option’, i.e. a \( (1 + z)^{-0.9} \) decline in space density at \( z > 4.8 \). As shown in Fig. 10, one possible way to avoid this is to remove the entire starburst population (i.e. the high-luminosity component) at \( z > 1.5 \) and we adopt this solution for our final model.

The removal of the high-redshift starburst component of the luminosity function implies that the evolving normal galaxy population in the simulation is sufficient to account for the star formation at these epochs. Although we used the terms ‘normal galaxy’ and ‘starburst’ merely as labels to refer to the two Schechter function components of the local luminosity function, this trend may find some physical justification in the work of Oberschckow & Rawlings (2009). The latter authors showed that, with increasing redshift, galaxy discs are smaller, leading to higher gas densities and pressures and hence higher molecular gas fractions and SFRs. In the local Universe, SFRs in excess of \( \sim 10 M_\odot \) \( yr^{-1} \) can only occur in dense gas discs created by zero angular momentum gas in major mergers characteristic of starburst galaxies, e.g. the merger-triggered local ULIRGs.

Even with the starburst cut-off in place, the modest (factor of \( \sim 2 \)) excesses of simulated sources at the bright flux ends of all three Spitzer bands persist, as shown in Fig. 11. In Fig. 12, we show the flux-redshift planes for the normal galaxy and starburst populations for 70 and 160 \( \mu m \) fluxes exceeding 100 mJy; much of the excess normal galaxy population occurs at redshifts \( z < 0.5 \), particularly at 70 \( \mu m \). It may arise from a combination of effects, such as a departure from strictly power-law PLE or from an inaccurate treatment of the scatter on the FIR relation in equation (1) [i.e. from galaxies scattered into the high-Z(FIR) Gaussian wing of the \( q \) parameter distribution]. In support of the first possibility, Huynh et al. (2007) found no evidence for significant evolution at infrared luminosities below \( 10^{11} L_\odot \) for redshifts \( z < 0.4 \).

A modest (factor of \( \sim 2 \)) deficit also persists in the 24 \( \mu m \) counts around 0.3 mJy, which suggests that the required template evolution may be more extreme than assumed, possibly requiring a dependence on luminosity in addition to redshift. It is also possible that the Rieke templates underestimate the PAH strength in the higher redshift galaxies.

Finally, we note that gravitational lensing biases (e.g. Negrello et al. 2007) are not accounted for in these simulations, but can be critical when the source counts are very steep.

4.3 Comparison with observed redshift distributions

Having achieved reasonable agreement with the Spitzer MIPS source counts, particularly at the faint end of the observed flux range, we now compare the redshift distributions. In Fig. 13, we show them for 24 \( \mu m \) sources above flux limits of 0.08, 0.15 and 0.3 mJy. The observational data were taken from Le Floch et al. (2009) and are based on photometric redshift analysis of 30 000 sources in a \( \sim 1.68 \) deg\(^2\) region of the COSMOS field. The simulated distributions were derived from a 0.25-deg\(^2\) region, and are in good agreement with the observations. We note, however, that Le Floch et al. excluded galaxies brighter than \( f_{AB} = 20 \) mJy to minimize cosmic variance fluctuations at low redshift. As they also remarked, the small cosmic volume covered by the observations below \( z < 0.4 \) prevents any useful comparison in this regime.

At 70 \( \mu m \), we compare with results from the COSMOS and GOODS-N fields (Fig. 14) using a 4-deg\(^2\) simulation area. The COSMOS results are based on photometric redshift analysis by Hickey et al. (in preparation) for a shallow field covering 1.43-deg\(^2\) and a deep subregion of 0.165-deg\(^2\). The deep field is complete to 10 mJy, but the shallow field is only 60 per cent complete at this flux level; in calculating \( dn/dz \) for the shallow field we compensated for this by weighting each source by \( 1/c(z) \), where \( c(z) \) is the completeness level at its flux, as read off from fig. 3 of Frayer et al. (2009). The shallow field \( dn/dz \) agrees better with the simulation at \( z < 0.4 \), whilst at \( z > 0.75 \) the match to the deeper field is more favourable. Redshift distributions for 70 \( \mu m \) COSMOS sources have also been compiled by Kartaltepe et al. (2010).

At a deeper flux level of 2 mJy, we compare with the raw redshift distribution derived by Huynh et al. (2007) for the 0.05-deg\(^2\) GOODS-N field, using a 0.25-deg\(^2\) simulation area; there is again a deficit of observed sources but the GOODS-N source catalogue is only \( \sim 50 \) per cent complete at the flux limit (see Frayer et al. 2006, table 1), and the raw redshift distribution of Huynh et al. (2007), their

---

**Figure 10.** Upper panel: 850 \( \mu m \) source counts for the final model of Section 4.2 as determined from a 4-deg\(^2\) simulation area; the observed SHADES counts are the same as in Fig. 6; the dashed line shows the contribution of the normal galaxies and the dot-dashed line represents the starbursts, assuming a sharp cut-off in the latter population at \( z > 1.5 \); the dotted line shows the contribution of the starbursts under the assumption of the ‘default post-processing’ cut-off in the space density, i.e. \( (1 + z)^{-0.9} \) at \( z > 4.8 \). Lower panel: 850 \( \mu m \) redshift distributions for flux limits of 2.4 and 5 mJy, assuming the \( z > 1.5 \) cut-off in the starburst population.
Figure 11. Spitzer MIPS source counts for the final model, after application of a luminosity boost (Section 4.1) and template evolution (Section 4.2) to the star-forming galaxies and with the starburst population removed at $z > 1.5$; symbols and observed data are as in Fig. 5.

Figure 12. Flux-redshift distributions for simulated normal galaxies and starbursts contributing to the excess differential source counts above 100 mJy in Fig. 11 at 70 and 160 $\mu$m, demonstrating that much of this excess arises from a local population at $z < 0.5$; determined using a shallow subset of the full $20 \times 20$ deg$^2$ input radio simulation.

The effects of cosmic variance for the small field observed may also be important. At 850 $\mu$m, the redshift distributions for flux limits of a few mJy (Fig. 10) have median redshifts at $z = 2–3$ and high-redshift tails extending beyond $z = 4$. Thus, even though the final model has eliminated the starburst (high $L$) population at $z > 1.5$, it is nevertheless able to reproduce the population of submillimetre (SCUBA) galaxies which reside on average at $z \simeq 2.3$, as deduced from spectroscopic (Chapman et al. 2005) and radio-mm-FIR photometric measurements (Aretxaga et al. 2007). There is also observational evidence that the distribution extends to redshift $z = 4$ and beyond (Coppin et al. 2009). This reinforces our earlier statement that the terms ‘normal galaxy’ and ‘starburst’, which we use to label the two Schechter function components of the $z = 0$ star-forming galaxy luminosity function, should not be invested with much physical significance beyond the local Universe.

4.4 Possible evolution in the FIR–radio correlation?

Our default assumption is that the luminosity boost introduced in Section 4.1 applies equally to the radio and infrared luminosities and that it thus reflects a modification to the cosmological evolution of the star-forming galaxy population as a whole. Indeed, as we show in Fig. 15, the 1.4 GHz source counts for the star-forming galaxies come into better agreement with the observations after the application of the luminosity boost. The relevant observations are taken from Seymour et al. (2008) and provide a break-down of the 1.4 GHz sources counts into contributions from AGN and star-forming galaxies, with the latter dominating below 0.1 mJy. With reference to the radio source counts in fig. 4 of W08, the increase in the star-forming galaxy contribution brings the total radio source count at 1.4 GHz into better agreement with the observations at this flux level. In light of this, the luminosity boost should be applied when using the simulated radio catalogues, as described in Appendix A.

© 2010 The Authors. Journal compilation © 2010 RAS, MNRAS 405, 447–461
Figure 13. Comparison of the predicted 24 μm redshift distributions for the final model of Section 4.2 (solid lines) in the central 0.25-deg² of the simulation with those measured in a 1.68-deg² region of the COSMOS field by Le Floc’h et al. (2009). The latter authors excluded galaxies brighter than $I_{AB} = 20$ mag to minimize cosmic variance fluctuations at $z < 0.4$.

Nevertheless, we cannot exclude the possibility that some contribution to $\Delta \log L(L, z)$ may arise from redshift evolution and non-linearity in the FIR-radio correlation. Observational evidence for redshift evolution is at present limited, as discussed in Section 3, but strong upward evolution in the relation is expected at $z > 3$ due to increased inverse Compton scattering off the cosmic microwave background (e.g. Murphy 2009). In the local Universe, there is evidence that the relation may become non-linear at low luminosities (e.g. Condon 1992; Yun et al. 2001; Best et al. 2005). Best et al. (2005) found that below $\log L(1.4 \text{ GHz}) = 22.5 \text{ W Hz}^{-1}$ the measured local radio luminosity function falls below that derived in the FIR. Such non-linearity could partially account for the luminosity boosting, but it would need to evolve strongly with redshift in order to match that required in Fig. 8.

At higher redshift, major contributions in this area are expected from Herschel surveys, as suggested by initial results from BLAST (Ivison et al. 2010). To compare with the latter, we show in Fig. 16 the simulated quantity $q_{24}$, defined analogously to equation (1) but with the FIR luminosity replaced by the rest-frame 8–1000 μm luminosity, $L(TIR)$, (equation 4 of Ivison et al.). The simulated values are in good accord with the value of $q_{24} = 2.41 \pm 0.2$ for the 250 μm-selected sample of Ivison et al. (2010), with no evidence of redshift dependence. Ivison et al. also determined $q_{70}$ for a sample derived by stacking at the positions of 24 μm sources and found tentative evidence for a decline of the form $(1 + z)^{-0.15 \pm 0.05}$, but we do not attempt to replicate the selection effects associated with the definition of this particular sample. The lack of redshift dependence in the simulated $q_{24}$ primarily reflects the redshift-invariance we assumed for the FIR–radio relation in equation (1), in conjunction with the only mildly non-linear dependence of $L(TIR)$ on $L(FIR)$ in Fig. 1.

For completeness, we also show in Fig. 16 the quantities $q_{24}$ and $q_{70}$ as functions of redshift, for comparison with those of the baseline model shown in Fig. 7. Reflecting the imposed template evolution, $q_{24}$ increases more strongly with redshift out to $z = 1$ than in the baseline model, whilst $q_{70}$ remains effectively constant out to $z = 1$.

5 PREDICTIONS FOR HERSCHEL SURVEYS

We now present some predictions for forthcoming Herschel surveys and a comparison with results from the BLAST mission which flew a prototype of the SPIRE instrument on a telescope half Herschel’s size. In Fig. 17, we show predicted integral source counts for surveys at 100, 250, 350 and 500 μm which correspond closely with those predicted by the backward-evolution model of Valiante et al. (2009). Also shown in this figure are normalized differential source counts at 250, 350 and 500 μm, which compare reasonably well with the BLAST counts as determined from the ‘P(D)’ analysis of Devlin et al. (2009) (see also Patanchon et al. 2009). At 250 and 350 μm, the model marginally exceeds the BLAST measurements in the highest flux bins, as also hinted at in the 160 μm comparison above $\sim 100 \text{ mJy}$. In Fig. 18, we compare with the ‘complete’ redshift distribution derived by Dunlop et al. (2009) for the 150 arcmin² GOODS-S field at 250 μm; the observed sample consists of 20 sources with redshifts down to a nominal flux limit of...
predicted redshift distributions exhibit broader peaks than those of L09, extending beyond \( z = 1 \); similarly, for HERMES Level 1 and 5 at 250 \( \mu \)m our distribution peaks just above \( z = 1 \) and that of L09 just below. At 100 and 160 \( \mu \)m in HERMES Level 5, we predict broad redshift distribution with a tail extending beyond \( z = 1 \) whereas L09 predict distributions strongly peaked at \( z = 0.2 \). For the ATLAS survey, the distributions of L09 exhibit marginally higher peaks than ours at \( z \leq 0.2 \); the L09 distributions cut-off sharply above \( z \sim 1.5 \), as do ours, due to the step function cut-off in the starburst population above \( z = 1.5 \).

6 CONCLUSIONS

We have post-processed the \( S^3 \)–SEX semi-empirical simulation of the extragalactic radio continuum sky (W08) to make predictions for Herschel surveys at FIR wavelengths. Existing observations in the mid-IR with Spitzer at 24, 70 and 160 \( \mu \)m and at 850 \( \mu \)m with SCUBA, together impose strong constraints on the assignment of infrared SEDs to the star-forming galaxies as a function of redshift. Our principal findings, incorporated into the final model, are as follows.

(i) In order to match the 70 \( \mu \)m counts, the star-forming galaxies are required to undergo stronger luminosity evolution than assumed by W08 for the radio simulation. It may be that W08 simply used an inaccurate evolutionary prescription based on the information available at that time; alternatively, it could be that there is genuine differential evolution between the FIR and radio populations, as a result of an evolving non-linearity in the FIR:radio correlation; the rest-frame 60–100 \( \mu \)m colour is assumed to evolve as log \( L_{60}/L_{100} \sim (1 + z)^{-2.5} \); beyond \( z = 1 \), this evolution must go into reverse in order not to overproduce the 850 \( \mu \)m source counts.

Our chosen model compares favourably with recent FIR survey results from BLAST. This inspires confidence in using it to make predictions for Herschel Key Programme surveys. Our predicted
source counts and redshift distributions correspond closely with those of Valiante et al. (2009) and L09, respectively, despite the clear differences in the methodologies of our models. This suggests that the combination of Spitzer mid-IR and 850 μm data impose strong constraints on the allowable model parameter space. Data products from our simulation are available on the S^3 website^7 and we expect them to serve as a valuable resource for the interpretation of Herschel surveys.

^7http://s-cubed.physics.ox.ac.uk

ACKNOWLEDGMENTS

RJW is supported by the Square Kilometre Array Design Study. MJJ acknowledges a Research Councils UK Fellowship.
Table 1. A selection of Herschel Key Programme surveys for which we provide dn/dz plots in Section 5.

| Survey                  | Area (deg$^2$) | Band (μm) | Depth (mJy) | Total f(z > 1)† | f(z > 2)†† |
|-------------------------|----------------|-----------|-------------|-----------------|------------|
| GOODS-Herschel          | 0.012          | 100       | 320         | 0.61            | 0.14       |
| Ultra-deep              | 160            | 460       | 0.69        | 0.25            |
| Hermes Level 1          | 0.11           | 250       | 1850        | 0.69            | 0.24       |
|                         | 350            | 1080      | 0.75        | 0.29            |
|                         | 500            | 680       | 0.82        | 0.37            |
| Hermes Level 5          | 27             | 100       | 11440       | 0.24            | 0.0018     |
|                         | 160            | 13420     | 0.41        | 0.033           |
|                         | 250            | 85700     | 0.63        | 0.18            |
|                         | 350            | 27000     | 0.69        | 0.24            |
|                         | 500            | 10470     | 0.79        | 0.34            |
| ATLAS                   | 600            | 100       | 59700       | 0.15            | 1.6E-04    |
|                         | 160            | 57170     | 0.30        | 8.3E-03         |
|                         | 250            | 165100    | 0.51        | 0.10            |
|                         | 350            | 28530     | 0.51        | 0.12            |
|                         | 500            | 5720      | 0.63        | 0.19            |

*Total number of simulated galaxies in survey area at $z = 1–4$.
†Fraction at $z > 1$.
††Fraction at $z > 2$.

REFERENCES

Appleton P. N. et al., 2004, ApJS, 154, 147
Archibald E. N., Dunlop J. S., Hughes D. H., Rawlings S., Eales S. A., Ivison R. J., 2001, MNRAS, 323, 417
Aretxaga I. et al., 2007, MNRAS, 379, 1571
Best P. N., Kauffmann G., Heckman T. M., Ivezić Z., 2005, MNRAS, 362, 9
Beswick R. J., Muxlow T. W. B., Thrall H., Richards A. M. S., Garrington S. T., 2008, MNRAS, 385, 1143
Buchanan C. L., Gallimore J. F., O'Dea C. P., Baum S. A., Axon D. J., Robinson A., Elitzur M., Elvis M., 2006, ApJ, 132, 401
Chapin E. L., Hughes D. H., Aretxaga I., 2009, MNRAS, 393, 653
Chapman S. C., Blain A. W., Smail I., Ivison R. J., 2005, ApJ, 622, 772
Cleary K., Lawrence C. R., Marshall J. A., Hao L., Meier D., 2007, ApJ, 660, 117
Condon J. J., 1992, ARA&A, 30, 575
Coppin K. et al., 2006, MNRAS, 372, 1621
Coppin K. et al., 2009, MNRAS, 395, 1905
Devlin M. J. et al., 2009, Nat, 458, 737
Dunlop J. S. et al., 2009, MNRAS, submitted (arXiv:0910.3642)
Eales S. et al. 2009, PASP, submitted (arXiv:0910.4279)
Farrah D. et al., 2008, ApJ, 677, 957
Frayer D. T. et al., 2006, ApJ, 647, L9
Frayer D. T. et al., 2009, AJ, 138, 1261
Gandhi P., Horst H., Snete A., Höning S., Comastri A., Gilli A., Vignali C., Duschl W., 2009, A&A, 502, 457
Garn T., Alexander P., 2009, MNRAS, 394, 105
Garn T., Green D. A., Riley J. M., Alexander P., 2009, MNRAS, 397, 1101
Grimes J. A., Rawlings S., Wilott C. J., 2004, MNRAS, 349, 503
Grimes J. A., Rawlings S., Wilott C. J., 2005, MNRAS, 359, 1345
Haas M., Willner S. P., Heymann F., Ashby M. L. N., Fazio G. G., Wilkes B. J., Chini R., Siebenmorgen R., 2008, ApJ, 688, 122
Hasinger G., 2008, A&A, 490, 905
Helou G., Khan I. R., Malek L., Boheme L., 1988, ApJS, 68, 151
Hernández-Caballero A. et al., 2009, MNRAS, 395, 1695
Huynh M. T., Frayer D. T., Mobasher B., Dickinson M., Chary R.-R., Morrison G., 2007, ApJ, 667, L9
Ivison R. J. et al., 2010, MNRAS, 402, 245
Kartaltepe J. S. et al., 2010, ApJ, 709, 572
Kauffmann G. et al., 2003, MNRAS, 346, 1055
Kim M., Ho L., Im M., 2006, ApJ, 642, 702

© 2010 The Authors. Journal compilation © 2010 RAS, MNRAS 405, 447–461
APPENDIX A: DESCRIPTION OF DATA BASE FORMAT

The simulated infrared fluxes are available from our online interactive data base at http://s-cubed.physics.ox.ac.uk/s3_sex. They are provided as supplementary columns to the Galaxies table, the first 16 columns of which contain the existing output from the W08 radio simulation. Each row of this table refers to an individual galaxy; multicomponent radio sources (i.e. FRI and FRII sources) are denoted by their core position and integrated radio fluxes. A description of the supplementary columns is given in Table A1.

In addition to the mid-IR and FIR flux densities (24–1200 μm), we also provide 2.2 μm K-band magnitudes. For the radio-loud AGN, the K-band magnitude is used to normalize the SED; for the radio-quiet AGN and star-forming galaxies, the K-band magnitude should be considered as schematic as no attempt was made to model accurately the stellar population and dust extinction at rest-frame optical wavelengths, even though the SED templates extend into this regime.

The RQ-AGN classification flag applies only to the radio-quiet (RQ)-AGN and specifies whether the source is classified as unobscured, Compton-thin or Compton-thick obscured, or whether it is part of the ‘excess’ population which is filtered out (as described in Section 2.2).

The Space-density filter flag indicates which sources have been filtered out due to the imposed cut-off in the space density at high-redshift. The infrared fluxes of all filtered-out sources are set to −999.

Δlog (L, z) is the luminosity boost which has been applied to the star-forming galaxies to generate the infrared fluxes, over and above the level set by the FIR:radio correlation. Note that the tabulated radio fluxes for the star-forming galaxies are the original values from W08, even though the boost may also be applicable to them, as discussed in Sections 4.1 and 4.4.

Table A1. Supplementary columns in the S3−SEX Galaxies table derived from the infrared extension to the radio simulation.

| Column | Attribute description |
|--------|-----------------------|
| 1–16   | Existing radio simulation output |
| 17     | log10(24 μm flux density) [Jy] |
| 18     | log10(70 μm flux density) [Jy] |
| 19     | log10(100 μm flux density) [Jy] |
| 20     | log10(160 μm flux density) [Jy] |
| 21     | log10(250 μm flux density) [Jy] |
| 22     | log10(350 μm flux density) [Jy] |
| 23     | log10(500 μm flux density) [Jy] |
| 24     | log10(850 μm flux density) [Jy] |
| 25     | log10(1200 μm flux density) [Jy] |
| 26     | 2.2 μm K-band magnitude |
| 27     | RQ-AGN classification flag: |
| 28     | (1) TYPE 1 (unobscured), |
| 29     | (2) TYPE 2 (Compton-thin obscured), |
| 30     | (3) TYPE 2 (Compton thick obscured), |
|       | (−1 = Source excluded |
|       | Δlog(L, z)† |

* Applies to radio-quiet AGN only.
† Applies to star-forming galaxies only.

This paper has been typeset from a T\(\text{\TeX}I\)/\(\text{\LaTeX}\) file prepared by the author.