JINGLE, a JCMT legacy survey of dust and gas for galaxy evolution studies - I. Survey overview and first results

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JINGLE, a JCMT legacy survey of dust and gas for galaxy evolution studies – I. Survey overview and first results


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ABSTRACT

JINGLE is a new JCMT legacy survey designed to systematically study the cold interstellar medium of galaxies in the local Universe. As part of the survey we perform 850 μm continuum measurements with SCUBA-2 for a representative sample of 193 Herschel-selected galaxies with $M_\ast > 10^9 M_\odot$, as well as integrated CO(2–1) line fluxes with RXA3m for a subset of 90 of these galaxies. The sample is selected from fields covered by the Herschel-ATLAS survey that are also targeted by the MaNGA optical integral-field spectroscopic survey. The new JCMT observations combined with the multiwavelength ancillary data will allow for the robust characterization of the properties of dust in the nearby Universe, and the benchmarking of scaling relations between dust, gas, and global galaxy properties. In this paper we give an overview of the survey objectives and details about the sample selection and JCMT observations, present a consistent 30-band UV-to-FIR photometric catalogue with derived properties, and introduce...
1 INTRODUCTION

The impact of large imaging and spectroscopic surveys on galaxy evolution studies has been substantial. Systematic observations of very large samples of galaxies at optical, ultraviolet (UV), and infrared (IR) wavelengths have, for example, allowed for precise measurements of stellar masses and star formation rates (SFRs) up to z ≳ 3. These measurements show how star-forming galaxies form a tight sequence in the SFR–M* plane whose shape is mostly redshift independent, but whose zero-point is shifted to ever higher SFRs as redshift increases (e.g. Noeske et al. 2007; Rodighiero et al. 2010; Whitaker et al. 2012).

Although such large surveys at UV-to-IR wavelengths have been standard practice for decades, folding millimetre (mm) and radio spectral line observations into such multiwavelength statistical studies is comparatively recent practice. New and improved instruments (e.g. multibeam receivers on radio telescopes, and sensitive receivers and backends fitted to mm/sub-mm dishes) have recently sped up the process of accumulating these challenging observations, making it possible to add atomic and molecular gas masses to the list of physical properties measurable over large, representative galaxy samples (e.g. Catinella et al. 2010; Saintonge et al. 2011; Tacconi et al. 2013). Such measurements have led to the understanding that galaxy evolution is driven to a large extent by the availability of cold gas in different galaxies at certain times and in particular environments, and, for example, can explain simply the redshift evolution of the main sequence (Saintonge et al. 2013; Sargent et al. 2014). Despite the technical challenges, further progress will only come from broadening the samples targeted for molecular gas studies, particularly focusing on galaxies with low stellar masses and objects beyond z ≈ 2.5.

While measurements of the mass and properties of the cold interstellar medium (ISM) are typically obtained via molecular and atomic line spectroscopy, it has become increasingly common practice to use far-infrared (FIR)/sub-mm continuum observations of galaxies to derive total dust masses, from which total gas masses are in turn inferred via the gas-to-dust ratio (e.g. Israel 1997; Leroy et al. 2011; Magdis et al. 2011; Eales et al. 2012; Sandstrom et al. 2012; Scoville et al. 2014; Groves et al. 2015). This method has generated significant interest, as it allows for gas masses to be measured for very large samples much more quickly and cheaply than via direct CO (and HI) measurements. The technique is of particular interest for low-mass and/or high-redshift galaxies with low metallicities, where it is known that CO suffers from photodissociation effects. However, there are many unknowns in this method that must be investigated before it can be applied reliably at high redshifts. For example, a simple linear relation between gas-to-dust ratio and metallicity is currently assumed, while there are indications of a large scatter at fixed metallicity and a possible redshift evolution (Galametz et al. 2011; Saintonge et al. 2013; Rémy-Ruyer et al. 2014; Accurso et al. 2017). Furthermore, the dust masses are estimated assuming that dust in all galaxies has properties similar to those in the Milky Way, which are now known not to be universally applicable (e.g. Gordon et al. 2003; Smith et al. 2012; Clayton et al. 2015).

There is therefore a pressing need for a systematic survey of the dust properties in a variety of galaxies to benchmark scaling relations with gas content as well as stellar, chemical, and structural properties. Such work will have profound implications not only for our understanding of gas and dust physics in nearby galaxies, but also for high-redshift work (either with the JCMT itself or with ALMA), where observers have to look beyond CO(1–0) spectroscopy to investigate the cold ISM. Finally, even if the dust properties resemble those in the Milky Way, estimating the dust masses from a relatively small number of photometric measurements using a method based on fitting the temperature T and opacity index β, as is commonly done, may suffer from systematic errors due to measurement errors, the assumed T-distributions being too simplistic (e.g. a single temperature, or only two distinct temperatures), and the T-dependence of β itself, as demonstrated in laboratory measurements (Mennella et al. 1998; Boudet et al. 2005; Coupeaud et al. 2011; Mutschke, Zeidler & Chihara 2013).

In this paper, we introduce the JCMT dust and gas In Nearby Galaxies Legacy Exploration, JINGLE, a new survey for molecular gas and dust in nearby galaxies. The main objectives of the survey are to provide a comprehensive picture of dust properties across the local galaxy population and to benchmark scaling relations that can be used to compare dust and gas masses with global galaxy observables such as stellar mass (M*), star formation rate (SFR), and gas-phase metallicity. After describing the sample selection and survey strategy, we present the extensive multiwavelength data products upon which JINGLE builds and the homogeneous catalogue of measurements derived from them. We also report on highlights from the survey’s early science papers.

Throughout this paper, we refer to accompanying JINGLE papers: Smith et al. (hereafter Paper II) describes the SCUBA-2 observations and data reduction process, Xiao et al. (hereafter Paper III) presents the data and first results based on the CO(2–1) observations, and De Looze et al. (hereafter Paper IV) presents the first JINGLE dust scaling relations.

All rest-frame and derived quantities assume a Chabrier (2003) IMF, and a cosmology with H0 = 70 km s⁻¹ Mpc⁻¹, Ω_m = 0.3, and Ω_Λ = 0.7.

2 SURVEY OBJECTIVES AND SAMPLE SELECTION

JINGLE is a SCUBA-2 survey at 850 μm of 193 galaxies, with about half of the galaxies also being observed in the CO J = 2–1 line [hereafter, CO(2–1)] using the RxA3m instrument. The sample consists of Herschel-detected galaxies probing the star formation main sequence above M* = 10⁸ M⊙ as illustrated in Fig. 1. Amongst several other data products, the JCMT observations importantly provide total, integrated molecular gas masses through the CO(2–1) line measurements as well as accurate dust masses from the modelling of the 850 μm and other infrared photometric points.

2.1 Science goals

JINGLE has been designed to achieve three broad scientific goals:
as stellar mass, metallicity, and star formation rate. Finally, these data are used to quantify how accurately the 250, 500, and 850 μm luminosities can be used to infer gas masses in low-redshift galaxies (Eales et al. 2012; Scoville et al. 2014; Groves et al. 2015). Understanding the nature and scatter of these correlations will provide a vital check on this technique, which is increasing in popularity at both low and high redshifts.

2.2 Sample selection

To achieve our science goals, we need to observe a statistically significant galaxy sample and obtain homogeneous data products with the JCMT, making use of both RxA3m and SCUBA-2. We also require the following ancillary multiwavelength data products:

(i) Herschel photometry to combine with the JCMT 850 μm fluxes to derive accurate dust masses, temperatures, and emissivities;

(ii) optical integral field spectroscopy (IFS) to derive spatially resolved (i.e. gradients) stellar and ionized gas properties, including metallicities;

(iii) H i observations (at the minimum integrated measurements, but ideally resolved maps) to quantify atomic gas masses within the same physical region of the galaxies as the CO and dust measurements.

We identified as the ideal fields the North Galactic Pole (NGP) region and three of the equatorial Galaxy And Mass Assembly (GAMA) fields (GAMA09, GAMA12, and GAMA15). These four fields are part of Herschel-ATLAS (H-ATLAS; Eales et al. 2010) and therefore have uniform, deep Herschel-SPIRE coverage, fulfilling our first requirement. The four fields are also all within the footprint of the MaNGA IFS survey, and the GAMA fields are further being covered by the Sydney-AAO Multi-object Integral-field spectrograph (SAMI), ensuring the availability of optical IFS information. Finally, all four fields are within the footprint of the Arecibo Legacy Fast ALFA Survey (ALFALFA) survey, so integrated H i masses are already available for about half of the galaxies, and an ongoing Arecibo programme (PI: M. Smith) is targeting all other JINGLE targets. In addition, the NGP is a high priority field for the blind Medium Deep Survey to be conducted at Westerbork with the new APERTIF phased array feed. As for the three GAMA fields, they lie within the footprint of WALLABY, an all-(southern) sky H i survey with the Australian Square Kilometer Array Pathfinder (ASKAP). Both of these large-scale blind H i surveys will give resolved H i maps on the time-scale of a few years.

We define as our parent sample for the selection of JINGLE targets all galaxies within our four fields that are part of the SDSS spectroscopic sample and have $M_* > 10^9 M_\odot$ and $0.01 < z < 0.05$. There are 2853 galaxies matching these selection criteria, out of which about half have been selected by MaNGA as possible targets. The distribution of the parent sample in the SFR–$M_*$ plane is shown in Fig. 1.

Out of this parent sample, we consider for JCMT observations those galaxies with a detection at the $3\sigma$ level at both 250 and 350 μm in the H-ATLAS survey. Given the depth of the H-ATLAS SPIRE maps and the sensitivity of SCUBA-2, a galaxy with a far-infrared continuum detectable at 850 μm before reaching the confusion limit would almost certainly be detected at both 250 and 350 μm. The requirement for H-ATLAS detections means that JINGLE targets are overwhelmingly selected from the blue star-forming galaxy population (Fig. 1).
shown to correlate well with the H I gas-to-stellar mass ratio, and as uniform coverage as possible of the SFR–detectable with SCUBA-2 in less than 2 h of integration. To have a selection criterion at 250 and 350 μm, a control object is selected at random within 0.1 dex in mass distribution a posteriori. This is a common procedure used by surveys such as GASS and MaNGA (e.g. Catinella et al. 2010). The final sample targeted for SCUBA-2 observation is presented in Fig. 1. The initial target selection was done using the stellar masses and SFRs released by Chang et al. (2015) and calculated with MAGPHYS (da Cunha, Charlot & Elbaz 2008) using GALEX and SDSS photometry, while in Figs 1 and 3 (and throughout this paper), we make use of the new stellar masses derived specifically by the JINGLE team using MAGPHYS again, but with our own 30-band multiwavelength catalogue (see Section 3). As will be shown in Fig. 6, the two sets of stellar masses follow each other linearly, with a systematic offset of 0.2 dex and a scatter of 0.15 dex. This explains why in the final JINGLE sample some galaxies have stellar masses just below 10^9 M⊙.

To test if the final JINGLE sample is biased towards particularly ISM-rich or dusty galaxies due to the selection criteria based on the Herschel/SPIRE photometry, we construct a control sample extracted from the parent sample of 2853 galaxies which is only mass- and redshift-selected from SDSS. For each JINGLE galaxy, a control object is selected at random within 0.1 dex in M∗ and 0.2 dex in SFR. The process is repeated 150 times to produce a family of control samples. To assess whether the JINGLE galaxies are particularly dusty, in Fig. 2 we compare the distribution of the JINGLE sample and one randomly chosen realization of the control sample in the parameter space formed by WISE 12 μm luminosity and FUV–Ks colour. Colours such as FUV–Ks or NUV–r have been shown to correlate well with the H I gas-to-stellar mass ratio, and therefore describe to which extent galaxies are ISM-rich (Catinella et al. 2013; De Vis et al. 2017). The Kolmogorov–Smirnov (KS) probability that the FUV–Ks distribution of the JINGLE and control samples are different, with the 68% confidence interval (0.23; such a result indicates that the JINGLE sample is not biased towards particularly ISM-rich galaxies.

However, as Fig. 2 shows, there is a tendency for some JINGLE galaxies to have higher 12 μm luminosities than their control objects. This is particularly evident for the redder population (FUV–Ks > 6). Similarly, among the blue population, there is a tail of control galaxies with L_{12μm} < 10^8 L⊙ which are mostly absent from the JINGLE sample, and vice versa. Indeed, the KS test, with a probability of 0.004 ± 0.002, confirms that the distributions of L_{12μm} of the JINGLE and control samples are different, with the JINGLE objects shifted towards higher IR luminosities (and therefore probably higher dust masses and/or stronger radiation fields). With an average normal FUV–Ks colours but elevated 12 μm luminosities, the JINGLE galaxies are possibly biased towards dust- or H2-rich systems at fixed H I mass; this will have to be carefully corrected for in upcoming analyses of dust scaling relations.

Out of the 193 galaxies targeted with SCUBA-2, a subset of 90 objects predicted to be detectable in less than 14 h of integration was selected to be observed with the heterodyne receiver RxA3m to obtain integrated CO(2–1) line fluxes. Galaxies that are part of the currently released MaNGA sample were given first priority for CO(2–1) observations, though all the galaxies selected for RxA3m observations are candidate MaNGA targets and likely to be part of future SDSS data releases. Fig. 3 illustrates the position of the sample selected for RxA3m observations in the SFR–M∗ plane.

### 2.3 JCMT observations

To plan for observations, predictions of 850 μm continuum and CO(2–1) line luminosities were made for all the galaxies in the
JINGLE parent sample. Extensive details about these calculations as well as descriptions of the observing strategy and the data products associated with the SCUBA-2 and RxA3m components of the survey are presented in Paper II and Paper III, respectively. A summary is presented here as an overview.

### 2.3.1 SCUBA-2

The sub-millimetre continuum observations for JINGLE are obtained with SCUBA-2, the 10 000 pixel bolometer camera operating at the JCMT (Holland et al. 2013). With two independent imaging arrays, SCUBA-2 can simultaneously map the sky at 450 and 850 μm. Given the availability of 500 μm fluxes from Herschel, and the significantly lower atmospheric transmission at 450 μm, the JINGLE survey is based on the requirement of detecting the continuum at 850 μm. However, as we simultaneously observe at 450 μm, for targets observed in better weather conditions there is the possibility of detecting higher resolution 450 μm dust continuum emission as well.

To prepare for the observations, a single modified blackbody with $\beta = 2$ was fitted to the Herschel fluxes; this fit was extrapolated to estimate the 850 μm flux. Given their angular sizes ($D_{25} = 20–50$ arcsec) as well as the 13 arcsec beam of SCUBA-2 at 850 μm, the JINGLE galaxies are marginally resolved in the maps. The integration time required for each galaxy to reach a 5σ detection was determined through the SCUBA-2 exposure calculator, taking into account the galaxy’s angular extent and assuming matched beam filtering and a range of weather conditions.

Observations are conducted in Daisy mode, which provides uniform coverage over a central 4 arcmin region with significant coverage out to 12 arcmin. The weather band (either grade 2, 3, or 4) was chosen so we would reach the required sensitivity in under 2 h. To achieve this, JINGLE was awarded 255 h of SCUBA-2 observing time, spread over weather bands 2, 3, and 4. The exact definition of the JCMT weather bands as a function of opacity at 225 GHz and levels of precipitable water vapour are available on the JCMT web pages.¹

### 2.3.2 RxA3m

The CO(2–1) line fluxes were estimated from the specific star formation rate of each object using the depletion time-scale and CO-to-H₂ conversion factor predicted by the 2-SFM formalism of Sargent et al. (2014). To validate these estimates, CO line fluxes were also extrapolated from the WISE 12 μm luminosities using the calibration of Jiang et al. (2015) and assuming a CO(2–1)/CO(1–0) line ratio of $r_{21} = 0.7$ and a CO-to-H₂ conversion factor $\alpha_{CO} = 4.35$ M⊙ (K km s⁻¹ pc²)⁻¹. The integration times are set by the requirement to detect the predicted line flux at the 5σ level over a spectral channel corresponding to 20 per cent of the expected (Tully–Fisher-inferred) line width. These integration times are calculated for weather bands 4 or 5 and the specific properties of the telescope and instrument.

The survey was granted 525 h of observing to complete the CO(2–1) observations, most of which is in band 5 to be used as a poor weather filler. At the frequency of the CO(2–1) line, the beam size is 20 arcsec, and given the angular size of the galaxies we observe in beam switching mode with a throw of 120 arcsec. The receiver bandwidth is 1000 MHz. Observations are monitored and reduced on a nightly basis. If a secure line detection is reached before the estimated required sensitivity is reached, observations of that galaxy are stopped. Otherwise, we continue observing the galaxy until the estimated sensitivity is reached. As is shown in Paper III, given the necessary integration time, reliable detections of the CO(2–1) line can be achieved for the JINGLE galaxies under such weather conditions after smoothing the spectrum to 30 km s⁻¹.

### 3 Ancillary Data Products and Derived Quantities

JINGLE relies not only on its own JCMT data products but also on the availability of several ancillary data sets across the electromagnetic spectrum. In particular, the availability of the far-infrared photometry from Herschel is key. Being a blind, wide-area survey of uniform depth with point source sensitivities of 7.4, 9.4, and 10.2 mJy (1σ total noise) at 250, 350, and 500 μm (Valiante et al. 2016), $H$-ATLAS is perfectly suited to provide the deep, uniform FIR photometry required to achieve the science objectives of JINGLE. Maps of the GAMA fields are provided by $H$-ATLAS data release 1 (Valiante et al. 2016) and the NGP field by data release 2 (Smith et al. 2017). The other external survey which is an integral part of the JINGLE strategy is MaNGA as it will provide two-dimensional (i.e. spatially resolved) measurements of the stellar mass surface density, kinematics, and chemical element abundance ratio for a significant fraction of the JINGLE galaxies for which CO(2–1) observations are conducted. However, as both JINGLE and MaNGA are ongoing surveys, the number of galaxies with both JCMT data products in the JINGLE Main Data Release (MDR) and MaNGA data products in SDSS DR14 (Abolfathi et al. 2018) is low, and joint analyses will therefore be the topic of future papers.

Here however, we make use of the abundant photometry available through $H$-ATLAS as well as a range of all-sky legacy surveys to construct a uniform multiwavelength flux catalogue for the JINGLE objects and derive important physical quantities such as stellar masses and star formation rates.

#### 3.1 Multiwavelength photometry

A key feature of JINGLE is the uniformity of the dust and gas measurements being gathered, since all the observations are conducted with the same instruments and to consistent depths. To best exploit this feature, it is essential that all physical parameters (stellar masses, SFRs, metallicities, etc.) are derived in a consistent manner. To this end, we have produced an extensive 30-band multiwavelength photometric catalogue. This catalogue makes use of data from 7 UV–submm facilities: the GALaxy Evolution eXplorer (GALEX; Morrissey et al. 2007), the Sloan Digital Sky Survey (SDSS; York et al. 2000; Eisenstein et al. 2011), the 2 Micron All-Sky Survey (2MASS; Skrutskie et al. 2006), the Visible and Infrared Survey Telescope for Astronomy (VISTA; Sutherland et al. 2015), the Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010), the Spitzer Space Telescope (Werner et al. 2004), and Herschel.

Table 1 summarizes important parameters for all these bands. All imagery was obtained from the official archives of each facility (except for the Herschel data, which is provided by Herschel-ATLAS); the data acquisition process was identical to that used in Clark et al. (2017).

The aperture–matched photometry was performed using the Comprehensive Adjustable Aperture Photometry Routine (CAAPR).²

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¹http://www.eaobservatory.org/jcmt/observing/weather-bands/

²https://github.com/Stargrazer82301/CAAPR.
pipeline, described in detail in Clark et al. (2017); CAAPR is a development of the photometry pipeline used in Clark et al. (2015) and De Vis et al. (2017).

Before being able to perform photometry, contamination from foreground stars in the UV–MIR bands was minimized using the star-removal code contained in the Python Toolkit for SKIRT (PTS; Camps et al. 2015). CAAPR removes any large-scale background structure (arising from cirrus, instrumental effects, etc.) by attempting to fit a fifth-order, two-dimensional polynomial to the map (with the target galaxy and other bright sources masked). If the fitted polynomial is found to be significantly different from a flat sky, then CAAPR subtracts the polynomial from the map before proceeding with the rest of the photometry.

To make fluxes directly comparable across bands, aperture-matched photometry is performed. For each galaxy, elliptical apertures were fit to the source in each band; these apertures were then compared and combined to produce a ‘master’ elliptical aperture that would enclose the source in every band. When performing this comparison, the sizes of the apertures were corrected to adjust for that would enclose the source in every band. When performing this comparison, the sizes of the apertures were corrected to adjust for the rest of the photometry.

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<th>Resolution FWHM (arcsec)</th>
<th>Calibration uncertainty (per cent)</th>
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Notes:
1. Morrissey et al. (2007).
4. SDSS DR12 Science Archive Server: https://dr12.sdss.org/home
5. VISTA Instrument Description: https://www.eso.org/sci/facilities/paranal/instruments/vircam/inst.html
6. VISTA Science Archive: http://vsa.roe.ac.uk/
8. NASA/IPAC Infrared Science Archive (IRSA): http://irsa.ipac.caltech.edu
11. Spitzer Heritage Archive (SHA): http://sha.ipac.caltech.edu/applications/Spitzer/SHA/
12. MIPS Instrument Handbook: https://irsa.ipac.caltech.edu/docs/SPITZER/docs/mips/mipsinstrumenthandbook/42/#_Toc288032317
13. PACS Instrument & Calibration Wiki: http://herschel.esac.esa.int/twiki/bin/view/Public/PacsCalibrationWeb
15. SPIRE Instrument & Calibration Wiki: http://herschel.esac.esa.int/twiki/bin/view/Public/Spire Calibration Web
using the master aperture, CAAPR convolves the aperture with each band’s beam by adding in quadrature the major and minor axes of the aperture ellipse to the PSF FWHM.

An annulus (with inner and outer major axes 1.25 and 1.5 times the major axis of the source aperture, and the same position angle and axial ratio as the source aperture) was used to find the local background, which was estimated using an iteratively sigma-clipped median. For maps with pixel width > 5 arcsec (i.e. the SPIRE bands) the flux inside apertures is measured with consideration for partial pixels. CAAPR determines the aperture noise associated with each flux value by randomly placing copies of the photometric apertures on the map around the source. All random apertures were positioned so as to avoid overlap with the actual source aperture as well as to avoid significant overlap with other random apertures. Although random, the apertures were biased towards being placed in regions of the map closer to the target source, according to a Gaussian distribution centered on the source coordinates. Fluxes in the random apertures were measured in the same way as for the source itself (i.e. including background annulus). The iteratively sigma-clipped standard deviation of these sky fluxes was taken as the aperture noise; this method thus incorporates instrumental noise and confusion noise.

For bands with beam FWHM > 5 arcsec, an aperture correction was applied to account for the fraction of the source flux spread outside the source aperture (and into the background annulus) by the PSF. Most instrument handbooks only provide such corrections for point sources, as corrections for extended sources (such as the JINGLE galaxies) require a model for the underlying unconvolved flux distribution. CAAPR assumes that each target galaxy, as observed in a given band, can be approximated as a two-dimensional Sérsic distribution convolved with the band’s PSF. Therefore CAAPR fits a two-dimensional PSF-convolved-Sérsic model to the map, and uses the (unconvolved) Sérsic distribution of the best-fitting model to estimate the factor by which the measured flux is altered by the PSF. This factor was used to correct the measured flux accordingly. When performing these convolutions we use the circularized PSF kernels3 of Aniano et al. (2011) for all bands (for consistency). The median value of the aperture correction in any given waveband, can be approximated as a two-dimensional Sérsic distribution. CAAPR assumes that each target galaxy, as observed in a given band, can be approximated as a two-dimensional Sérsic distribution convolved with the band’s PSF. Therefore CAAPR fits a two-dimensional PSF-convolved-Sérsic model to the map, and uses the (unconvolved) Sérsic distribution of the best-fitting model to estimate the factor by which the measured flux is altered by the PSF. This factor was used to correct the measured flux accordingly. When performing these convolutions we use the circularized PSF kernels3 of Aniano et al. (2011) for all bands (for consistency). The median value of the aperture correction in any given waveband, can be approximated as a two-dimensional Sérsic distribution. CAAPR assumes that each target galaxy, as observed in a given band, can be approximated as a two-dimensional Sérsic distribution convolved with the band’s PSF. Therefore CAAPR fits a two-dimensional PSF-convolved-Sérsic model to the map, and uses the (unconvolved) Sérsic distribution of the best-fitting model to estimate the factor by which the measured flux is altered by the PSF. This factor was used to correct the measured flux accordingly. When performing these convolutions we use the circularized PSF kernels3 of Aniano et al. (2011) for all bands (for consistency). The median value of the aperture correction in any given waveband, can be approximated as a two-dimensional Sérsic distribution. CAAPR assumes that each target galaxy, as observed in a given band, can be approximated as a two-dimensional Sérsic distribution convolved with the band’s PSF. Therefore CAAPR fits a two-dimensional PSF-convolved-Sérsic model to the map, and uses the (unconvolved) Sérsic distribution of the best-fitting model to estimate the factor by which the measured flux is altered by the PSF. This factor was used to correct the measured flux accordingly. When performing these convolutions we use the circularized PSF kernels3 of Aniano et al. (2011) for all bands (for consistency). The median value of the aperture correction in any given waveband, can be approximated as a two-dimensional Sérsic distribution.


Figure 4. Example of the data products available as part of the JINGLE multiwavelength dataset and the MDR catalogue. Left: 1 arcmin × 1 arcmin SDSS image centred on the position of the galaxy JINGLE25 (SDSSJ130636.39+275222.6). Centre left: UV-to-FIR spectral energy distribution of this galaxy from the CAAPR photometric catalogue. The best-fitting MAGPHYS model is shown as the grey line, as are the fits to the data points with λ > 30 μm using the templates of Chary & Elbaz (2001) renormalized following Hwang et al. (2010) (CE01; red line), and the hybrid AGN+SF templates of Mullaney et al. (2011) as implemented in Hwang & Geller (2013) (JRM; blue line). Centre right: JCMT SCUBA-2 continuum image of JINGLE25 at 850 μm, 2.5 arcmin × 2.5 arcmin. The white ellipse shows the shape and position of the aperture used to measure the flux, while the region between the two green ellipses is used to determine the background. Right: JCMT RxA3m spectrum of this same galaxy, centred on the frequency of the CO(2–1) line.
Figure 5. Comparison between the different SFR estimates calculated for the JINGLE sample using the CAAPR photometry, and those from SDSS photometry as retrieved from the MPA/JHU catalogue. See Section 3.2 for a description of the different SFR models. Dotted lines show a 1:1 relation and solid lines show a linear fit to the data, with the best-fitting slope ($m$), intercept ($b$), and scatter ($\sigma$) given in each panel. Individual galaxies are colour-coded by sSFR.

We briefly explain the different methods implemented with the CAAPR photometry. These are all compared against each other, and with the SDSS values, in Fig. 5. We have calculated three different flavours of SFRs within the first category; they all work by estimating separately SFR$_{UV}$ and SFR$_{IR}$ and taking the sum of the two as the total SFR:

(i) FUV+CE01: SFR$_{UV}$ is obtained directly from the GALEX FUV luminosity using the calibration presented in Kennicutt & Evans (2012) and SFR$_{IR}$ is obtained by fitting the templates of Chary & Elbaz (2001) for star-forming galaxies to all photometric data points with $\lambda > 30 \mu$m, allowing renormalization of the templates following Hwang et al. (2010).

(ii) FUV+JRM: SFR$_{UV}$ as above, but SFR$_{IR}$ is obtained using the templates of Mullaney et al. (2011) to all photometric points with $\lambda > 20 \mu$m as done in Hwang & Geller (2013). The main difference with CE01 is that these templates take into account a possible AGN contribution to the FIR fluxes.

(iii) FUV+12 $\mu$m: SFR$_{UV}$ is here calculated from the GALEX FUV flux using the calibration of Schiminovich et al. (2007), while SFR$_{IR}$ is derived from the WISE 12 $\mu$m fluxes using the calibration of Jarrett et al. (2013) and including a correction for stellar contamination using the WISE 3.4 $\mu$m fluxes following Ciesla et al. (2014). A description and analysis of this method is presented in Janowiecki et al. (2017). Unlike the others above, this SFR estimate is free of assumptions on the shape of the IR spectral energy distribution, although the related downside is that it does not consider possible systematic variations of the IR SED across the galaxy population (e.g. Nordon et al. 2012; Boquien et al. 2016).

The second category of SFRs are estimates obtained with two codes which use simple stellar population templates and models for the dusty ISM to reproduce the full SEDs of galaxies. First, MAGPHYS (da Cunha et al. 2008) was used to derive SFRs. MAGPHYS is a panchromatic SED fitting tool capable of modelling the stellar and dust emission in galaxies under the assumption of a dust energy balance (i.e. the stellar energy that has been absorbed by dust is assumed to be re-emitted in the infrared). The stellar emission is modelled using Bruzual & Charlot (2003) stellar population models, assuming a Chabrier (2003) IMF. The evolution of different stellar populations is calculated based on an analytic prescription of a galaxy's star formation history (SFH) represented as an exponentially declining star formation rate with some randomly imposed uncertainties.
bursts. Dust attenuation of these stars is modelled using the two-phase model of Charlot & Fall (2000), and differentiates between young stars (<10^7 yr) in dense molecular clouds attenuated by dust in their birth clouds and the ambient ISM dust, and older stars which only experience attenuation from the ambient ISM dust. The dust emission consists of the combined contribution of dust in birth clouds and in the ambient ISM. The dust emission in birth clouds is modelled using pre-defined templates for the emission of PAHs and transiently heated hot grains, and a modified blackbody (MBB) function with dust emissivity index $\beta = 1.5$ and dust temperature $T_d$ between 30 and 70 K for the emission of warm dust grains. An additional cold dust component (with $\beta = 2$ and $T_d$ between 10 and 30 K) is considered to model the dust emission from the ambient ISM. The latter temperature ranges correspond to the extended ISM.

To model the dust emission, GRASIL considers three components: transiently heated hot grains, and a modified blackbody (MBB) model is derived from the libraries of 25 000 stellar population models and 50 000 dust emission spectra. Since the templates for the optical part of the SED fitting come from Bruzual & Charlot (2003), the model should not be biased against passive galaxies, an advantage over some of the methods described above. The best-fitting models can be seen for all the JINGLE galaxies in Appendix A.

In addition, we applied GRASIL (Silva et al. 1998) to all the SEDs; this code also includes templates suitable for a broad range of galaxies as well as the effects of dust. The templates used are from Iglesias-Páramo et al. (2007) and the fitting technique is described in more detail in Michalowski, Hjorth & Watson (2010). In brief, GRASIL is an SED fitting tool including radiative transfer that is coupled to a chemical evolution code (CHE_EVO, Silva 1999) and models the SFH of galaxies following a Kennicutt–Schmidt-type law (Schmidt 1959; Kennicutt 1998b): $SFR(t) = \nu M_\ast(t)^k$, where $k = 1$ and $\nu$ is a free parameter. The star formation rate is thus regulated by the gas mass which depends on the infall of primordial gas with a rate that is proportional to $\exp(-t/\tau_{\text{inf}})$, where the timescale $\tau_{\text{inf}}$ is a free parameter ranging between 0.1 and 2.16 Gyr. To mimic a recent burst of star formation, an extra star formation law with a declining time-scale of 50 Myr has been added to the SFH. To model the dust emission, GRASIL considers three components: star-forming giant molecular clouds (GMCs), stars that have already emerged from their birth clouds, and diffuse gas. The time-scale for stars to escape from molecular clouds, $\tau_{\text{esc}}$, is a free parameter of the model (varied from 1 to 4 × 10^7 yr). Galaxies are modelled to have an age of 13 Gyr and an exponential disc geometry with scalelength of 4 kpc and scaleheight of 0.4 kpc with a range of inclinations (15, 45, and 75°). The dust-to-gas ratio is assumed to be proportional to the metallicity. The dust emission from each galaxy geometry is then calculated with a radiative transfer code. The dust masses from GRASIL have been derived based on average dust opacities in the Optical depths of our galaxies are typically 20–60 arcsec. These aperture corrections could explain some of the scatter compared with methods that use the integrated flux from the galaxies.

As shown in Fig. 5, there is generally good agreement between all possible pairs of SFR indicators with scatter in the range of 0.1–0.3 dex. As expected, the tightest correlations are seen between indicators that are closely related, such as FUV+CE01 and FUV+JRM. The largest scatter is observed in the comparisons that involve the MPA/JHU spectral values. For these nearby galaxies, aperture corrections have to be applied to these spectral measurements as the SDSS fibres cover 3 arcsec while the optical diameters of our galaxies are typically 20–60 arcsec. These aperture corrections could explain some of the scatter compared with methods that

3.3 Stellar masses

We have calculated stellar masses for all JINGLE galaxies from the CAAPR photometry as part of the MAGPHYS and GRASIL fitting. Additionally, the CAAPR-measured WISE 3.4 μm luminosities are used to estimate $M_\ast$ by assuming a constant mass-to-light ratio of 0.47 (McGaugh & Schombert 2014). In Fig. 6, these stellar masses are compared with three alternative estimates:

(i) SDSS/WISE MPHYS: from Chang et al. (2015), an independent determination of $M_\ast$ using MAGPHYS, making use of SDSS and WISE photometry

(ii) MPA/JHU: from the MPA-JHU catalogue, these $M_\ast$ values are based on the SDSS photometry and calculated following Salim et al. (2007)

(iii) SDSS Wisc/BC03: these $M_\ast$ values are retrieved from the SDSS DR10 database, and have been calculated using the PCA-based method of Chen et al. (2012) and stellar population models from Bruzual & Charlot (2003)

The scatter between pairs of different $M_\ast$ measurements is in the range of 0.1–0.3 dex. The scatter is largest and the relations farthest from linear when comparing any mass estimate with the one calculated from the WISE 3.4 μm luminosities, suggesting that the assumption of a constant mass-to-light ratio is not appropriate across the JINGLE sample, or that dust is a contributor to the 3.4 μm luminosities (Meidt et al. 2014). In the rest of this paper we adopt the values of $M_\ast$ from MAGPHYS and the CAAPR photometry, but all other estimates are also made available as part of the public data release to ease comparison with other samples.

3.4 Derived products catalogue

In addition to the stellar masses and star formation rates described in Section 3, we have compiled and calculated an extensive set of measurements for the JINGLE galaxies, as the survey science
Objectives revolves around understanding the interplay between gas, dust, and a broad range of galaxy properties. As part of the JINGLE MDR, we release the derived products catalogue for all 193 JINGLE galaxies. In addition to JINGLE catalogue IDs and SDSS name, coordinates, and spectroscopic redshift, the key quantities presented in Table 2 are:

(i) $M_*$: the stellar masses estimated with MAGPHYS and our CAAPR photometric catalogue. The median statistical uncertainty on $M_*$ is 0.055 dex and the systematic uncertainty is $\sim 0.15$ dex, as estimated from the scatter between the MAGPHYS results and other stellar mass estimations as shown in Fig. 6.

(ii) $r_{50}$: the SDSS $r$-band Petrosian radius, in units of kiloparsec.

(iii) $\mu_*$: the stellar mass surface density calculated as $\mu_* = M_*/(2\pi r_z^2)$, where $r_z$ is the Petrosian half-light radius in the $z$ band in units of kiloparsec. This quantity correlates with morphology, with $\log \mu_* = 8.7$ the empirical threshold where galaxies go from being disc- to bulge-dominated.

(iv) $C$: the concentration index defined as the ratio of the SDSS $r$-band Petrosian $r_{90}$ and $r_{50}$. It is a measure of how centrally concentrated the light of the galaxy is with values above 2.5 indicative of a significant stellar bulge contribution to the total light.

(v) $M$: galaxy morphology as determined from Galaxy Zoo 1 (GZ1; Lintott et al. 2011), or from KIAS value-added galaxy catalogue (Choi, Han & Kim 2010) and our own visual classification if not available in GZ1 (1: spiral, 2: elliptical). The vast majority of the galaxies in the JINGLE sample are spirals. Alternative morphology information based on automated classifications or bulge/disc profile fitting, and for example differentiating between early- and late-type spirals, are also available elsewhere (e.g. Huertas-Company et al. 2011; Simard et al. 2011).

(vi) SFR: the star formation rate obtained with MAGPHYS and the CAAPR photometric catalogue. The median statistical uncertainty on SFR is 0.03 dex and the systematic uncertainty is $\sim 0.2$ dex, as estimated from the scatter between the MAGPHYS results and other SFR estimations as shown in Fig. 5.

(vii) $12+\log (O/H)$: gas-phase metallicity calculated from optical strong emission lines measured in the SDSS spectra using the O3N2 calibration of Pettini & Pagel (2004, hereafter PP04). In cases where the emission lines are not all detected or where their excitation is likely to be influenced by the presence of an AGN (see column ‘BPT’), then we use the value derived from the mass–metallicity relation as derived by Kewley & Ellison (2008) to be on the same PP04 scale.

Figure 6. Comparison between the different stellar mass estimates calculated for the JINGLE sample using the CAAPR photometry, and those from SDSS photometry as retrieved from the DR10 database. See Section 3.3 for a description of the different SFR models. Dotted lines show a 1:1 relation and solid lines show a linear fit to the data, with the best-fitting slope ($m$), intercept ($b$), and scatter ($\sigma$) given in each panel. Points are colour-coded according to specific star formation rate as in Fig. 5.
Table 2. Properties of the JINGLE galaxies. (The full table is available electronically.)

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<th>(\log SFR) ((\text{M}_\odot) yr(^{-1}))</th>
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(viii) BPT: galaxy classification based on SDSS optical emission
line flux ratios using the criteria of Baldwin, Phillips & Terlevich (1981), Kewley et al. (2001), and Kauffmann et al. (2003) (−1: undetermined, 0: inactive, 1: star forming, 2: composite, 3: LINER, 4: Seyfert). The galaxies are not selected in any way based on the presence or not of an active nucleus, and therefore the sample does not contain any bright (and thus rare) AGN, although 14 of the galaxies are classified as LINER or Seyfert.

(ix) Env: environment classification based on the information in
the group catalogue of Tempel et al. (2014) (0: no data, 1: isolated, 2: central, 3: satellite).

The full version of Table 2 including all 193 galaxies is available in electronic format and on the JINGLE data release page.7

4 JINGLE MAIN DATA RELEASE

Observations for JINGLE at the JCMT began in 2015 December,
with the SCUBA-2 component of the survey completed in 2018 February. Due to particularly good weather conditions throughout
the winter of 2016 owing to an El Nino effect, the completion
rate of the RxA3m observations, which are designed to be con-
ducted in poorer weather conditions, remained lower. By the time
the RxA3m receiver was decommission in 2018 June, we had com-
pleted observations of 63/90 of the intended targets. This completed
sample includes all the higher priority MaNGA objects. We there-
fore include in the JINGLE MDR all 193 SCUBA-2 observations
and CO(2–1) observations for 63 of these galaxies. The remaining
galaxies selected for CO observations will be observed as soon as
a replacement receiver is installed on the JCMT (expected in 2019)
and those data made public in due course in an Extended Data
Release.

4.1 SCUBA-2

The SCUBA-2 data are reduced within the Starlink environment
(Currie et al. 2014) using a custom-made pipeline for the speci-
ficities of the JINGLE observations. Extensive simulations were
performed to develop this pipeline, in particular to fully charac-
terize the impact of filtering, and investigations made to find the
most appropriate standard flux calibration factor (Dempsey et al.
2013). Total 850 μm fluxes are measured through aperture pho-
tometry, with apertures determined through a joint analysis of the
Herschel-SPIRE photometry based on the method describe in Smith
et al. (2017). The full details of the SCUBA-2 observations and data
reduction are given in Paper II.

The properties of the sample of galaxies with SCUBA-2 observa-
tions is summarized in Fig. 7. The overall detection rate at 850 μm
is 64 per cent (3σ detections), but the non-detections do not cluster
in any particular region of parameter space. As part of our MDR,
we release the 850 μm maps all 193 JINGLE galaxies with
without matched filtering applied. An example of the 850 μm im-
age of galaxy JINGLE25 is shown in Fig. 4. In addition, the MDR
catalogue presented in Paper II includes the fluxes measured from
consistent aperture photometry on both our new SCUBA-2 images
and the Herschel PACS and SPIRE images. As explained in
Section 5, these far-infrared and sub-millimetre measurements are
combined to carefully constrain the dust properties of the JINGLE
galaxies.

5 EXAMPLE SCIENCE

We present some short highlights of science enabled by JINGLE, all
of which will be revisited in more depth in the data release papers
and subsequent science analysis papers.

5.1 The relation between CO line luminosity and the FIR continuum

Although measurements of the cold interstellar medium are typi-
cally obtained via molecular and atomic line spectroscopy, several

7http://www.star.ucl.ac.uk/JINGLE/data.html.
recent studies have derived total gas masses via a gas-to-dust ratio combined with far-infrared/sub-mm continuum measurements of total dust masses (e.g. Israel 1997; Leroy et al. 2011; Magdis et al. 2011; Eales et al. 2012; Sandstrom et al. 2012). There are also suggestions that the luminosity in particular FIR bands, such as 500 or 850 μm, could be extrapolated directly to a total molecular gas mass without the need to first estimate a dust mass (Scoville et al. 2014; Groves et al. 2015; Scoville et al. 2016). These methods are generating significant interest, as they allow gas masses to be measured quickly for very large samples, for example in high-redshift galaxy surveys. Uncertainties related to these methods involve the dependence of the gas-to-dust ratio on metallicity and changes in the physical properties of the dust grains with environment and/or redshift. Dust masses are typically estimated using Milky Way-like dust properties (Draine & Li 2007) and a simple linear relation between gas-to-dust ratio and metallicity (Leroy et al. 2011).

JINGLE will be able to investigate these assumptions and calibrate the empirical relation to estimate gas masses based on FIR/submm continuum. We begin here by investigating the relation between CO(2–1) line luminosity and 850 μm luminosity for those 63 galaxies in MDR which have both SCUBA-2 and RxA3m observations. Fig. 9 shows this relation through measuring the 850 μm flux that is coming from the area equivalent to the RxA3m beam at the frequency of the CO(2–1) line. Not surprisingly, there is a clear and near-linear correlation between the two sets of luminosities, in agreement with the sample compiled by Scoville et al. (2016), where we have assumed a CO(2–1)/(1–0) line ratio of r_{21} = 0.8 (Saintonge et al. 2017) to compare the samples directly.

The relation between 850 μm and CO line luminosity calibrated by Scoville et al. (2016) using a sample of bright nearby star-forming and starburst galaxies is linear in logarithmic space. The JINGLE galaxies as shown in Fig. 9 suggest a change in the relationship at the low-luminosity end, which is also where the lowest mass (and therefore lowest metallicity) galaxies reside. Fitting to all the galaxies in the JINGLE DR1 sample while carefully accounting for upper limits and measurement errors, we find the relation to be superlinear with log L_{CO(2-1)} = 1.372logL_{850}-1.376. In particular, Fig. 9 suggests that low-mass (and lower metallicity) galaxies are underluminous in CO(2–1) relative to their 850 μm emission. Any deviation from a linear dependence or any second parameter dependence in the L_{CO}-L_{850} relation will be investigated by JINGLE, and further discussion of the correlations between CO luminosity and monochromatic submillimetre fluxes will be presented in Paper III.

5.2 Dust SED modelling

The new SCUBA-2 850 μm observations, in combination with the ancillary WISE 12, 22 μm, IRAS 60 μm, and Herschel 100, 160, 250, 350, and 500 μm data for JINGLE galaxies, result in an exceptionally well-sampled dust spectral energy distribution, extending from the stochastically heated grains probed at mid-infrared wavelengths to the warm and cold dust components emitting in far-infrared and sub-millimetre wavebands. This broad wavelength coverage makes the JINGLE sample a unique laboratory to study the multitemperature dust reservoirs hosted by galaxies and to probe variations in a galaxy’s dust grain properties. To exploit this unique wavelength coverage, we use a set of different types of dust SED models to uncover the nature of grain populations and investigate possible grain property variations with the metallicity, stellar mass, and (specific) star formation rate of JINGLE galaxies.
In a first paper (Paper IV), we model the dust emitted from NIR to submm wavebands with The Heterogeneous dust Evolution Model for Interstellar Solids (THEMIS) dust model (Jones et al. 2013; Köhler, Jones & Ysard 2014; Jones et al. 2017). The THEMIS dust composition consists of hydrogenated amorphous carbons, (a-C:H) and silicates with iron nano-particle inclusions (a-SilFe). The optical constants for these grain species were derived from laboratory studies and the size distribution and grain abundances were constrained from the observed dust extinction and emission in the Milky Way. We study variations in the relative grain abundances of small (sCM20) and large hydrocarbons (lCM20) and silicate-type grains (sil) across the sample of JINGLE galaxies and determine the strength of the radiation field heating these grains, $G$, relative to the radiation field characteristic of the solar neighbourhood, $G_0$. Fig. 10 shows an example of a best-fitting SED with the THEMIS dust model for JINGLE 147, and is representative of the type of modelling applied to the entire JINGLE sample in Paper IV. We will study how the total dust mass and relative grain abundances change depending on whether the SCUBA-2 850 μm observations are used to constrain the dust SED. We will furthermore present dust scaling relations for the entire JINGLE galaxy sample and compare them with other nearby galaxy samples to infer how ‘dusty’ JINGLE galaxies are (see also Fig. 2).

In a second paper (Lamperti et al. in preparation, hereafter Paper V), we model the JINGLE dust emission using a variety of MBB functions to infer how the dust mass, $M_d$, effective dust emissivity index, $\beta_{\text{eff}}$, and dust temperature, $T_d$, vary among the JINGLE sample. The effective dust emissivity index $\beta_{\text{eff}}$ is sensitive to the Rayleigh–Jeans slope of the dust SED and its peak position. The slope depends on the dust emissivity of grains which is directly linked to the composition and size of grains. A Bayesian fitting algorithm is used to derive the best-fitting model parameters for a set of different dust SED models. We adopt the three models employed by Gordon et al. (2014) for the SED fit of the Magellanic Clouds: single modified blackbody (SMBB), two modified blackbodies (TMBB), and broken emissivity law modified blackbody (BMBB). Fig. 11 shows representative SED fits using the SMBB, BMBB, and TMBB models for JINGLE 147. We assumed a constant value of $\kappa_0 = \kappa(500 \, \mu m) = 0.051 \, m \, kg^{-1}$ from Clark et al. (2016) in the SED fitting. More details about the dust SED modelling can be found in Paper V. We will also compare non-hierarchical and hierarchical Bayesian fitting algorithms, and study the effect of these different methods on the $T_d$–$\beta$ relation for JINGLE galaxies. The factor of 4 offset in the dust mass derived with the THEMIS dust model and the MBB models for JINGLE 147 is largely attributed to the different dust opacities assumed in both models, and will be further explored in Papers IV and V.

5.3 Background sources

While the JINGLE SCUBA-2 observations are designed to measure the emission from targeted galaxies, their field of view is significantly larger, allowing for a blind survey of background objects. Over the 193 fields observed as part of JINGLE, the total area mapped by SCUBA-2 is around 10.1 deg$^2$. However, this includes the edges of the maps, which typically have much higher noise than the centre, so our fields are not uniform. We can restrict ourselves to ‘good’ pixels by selecting only pixels with instrumental noise resulting in a mean uncertainty of 1.6 mJy beam$^{-1}$ or less, comparable to that seen in the S2 Cosmology Legacy Survey (S2-CLS, Geach et al. 2017), which covered 2.2 deg$^2$. Under this restriction, the total area covered by JINGLE is 1.05 deg$^2$. The highlight
results presented below were however derived from the first 105 fields observed by JINGLE, corresponding to a high sensitivity area of 0.57 deg$^2$.

To measure the 850 $\mu$m fluxes, $F_{850}$, of sources other than the main JINGLE targets, we first convolved the maps with a matched filter of 13 arcsec diameter, equal to the SCUBA-2 beam at 850 $\mu$m. We then selected all sources with a peak signal to noise ratio of 4 or more in this convolved map and extracted the 850 $\mu$m flux at these positions using aperture photometry on the raw maps. An aperture of 13 arcsec radius was used to extract the source flux, with an annulus of inner radius 13 arcsec and outer radius of 26 arcsec used to extract a background estimate, which was removed from the source flux. No further corrections have been made at this stage. The positions of the 850 $\mu$m sources were then used to extract sources on the Herschel 250, 350, and 500 $\mu$m maps from H-ATLAS. This process results in a total of 119 sources detected across the 105 maps.

As a first look, in Fig. 12 we compare our results from all 119 sources to the number counts of 850 $\mu$m sources from the $\sim$2.2 deg$^2$ S2-CLS and to $\sim$0.5 deg$^2$ deep images of the COSMOS field (Casey et al. 2013). Even without any correction, we find there is generally good agreement between our observations and the other fields. At the high flux end we appear to detect more objects. This is to be expected, as our observations target local galaxies as opposed to random fields. The black dashed line indicates our approximate detection threshold cutoff of 6.4 mJy, and below this we detect fewer sources relative to the blank field number counts, as expected.

5.3.1 Overdensities of sources

To focus purely on background sources, we selected all sources that are at a distance of at least 40 arcsec (approximately three times the FWHM of the SCUBA-2 beam) from the central galaxy that was targeted. Of our 119 sources, 79 fulfil this criteria. In the JINGLE6 field, we detect eight SCUBA-2 sources to at least a 4$\sigma$ level, some of which are shown in Fig. 13. Their fluxes vary between 3.7 and 7.5 mJy, with a mean of 6.0 $\pm$ 1.3 mJy. One is associated with the central galaxy and one appears to be associated with the $z = 0.0159$ galaxy 2MASX J13232557+3206115, but the other six do not appear to be associated with any optical source.

Using the 850 $\mu$m number counts from Geach et al. (2017), and counting those sources with an 850 $\mu$m flux greater than 6.3 mJy, we expect to detect $\sim$175.8 $\pm$ 4.7 sources deg$^{-2}$. In the 0.02 deg$^2$ of JINGLE6, we detect five sources with an 850 $\mu$m flux greater than 6.3 mJy, two of which are associated with local galaxies. Converting this to a number counts estimate (without corrections) would result in 252.1 $\pm$ 15.9 sources deg$^{-2}$, a 4.8$\sigma$ overdensity. Given that two of our sources appear to be associated with local galaxies, this is unlikely to be a physical cluster of 850 $\mu$m sources, and is more likely to be merely a line of sight overdensity. We note, however, that 2MASX J13232557+3206115 is classed as an elliptical galaxy, and is unlikely to have a significant infrared flux. No source is detected at this position in the Herschel 250, 350, or 500 $\mu$m maps, though a $\sim$2$\sigma$ 500 $\mu$m flux of 12 mJy does appear $\sim$10 arcsec away from the nominal position, within the size of SPIRE’s 500 $\mu$m beam. It
is therefore possible that this source is lensing a background source or that there is a chance overlap between this local galaxy and a background SMG. Other fields, such as JINGLE21 and JINGLE91, also show mild overdensities at a few 250 μm, but JINGLE6 appears to be the most overdense of the 105 JINGLE fields studied for background sources so far.

5.3.2 Quasars

The quasar B2 1310+31 at $z = 1.055$ (Colla et al. 1970) is detected to a 250 μm level with $F_{250} = 24.6 ± 1.2$ mJy. This source is not detected in the Herschel 250, 350, or 500 μm maps. A non-detection with Herschel is not surprising, as the source has a reasonably flat spectrum and Herschel’s detection limit is around 20 mJy. The 850 μm flux is consistent with the radio flux of this flat spectrum source.

5.3.3 850 μm risers: high-redshift candidates?

Michałowski et al. (2017) find that 20–25 per cent of 850 μm sources with S/N ≥ 4 are not identified in other bands. In their estimate of the redshifts of these sources, they find they are typically at $z > 2$, greater than those of 850 μm sources with counterparts in optical/NIR or Herschel bands (c.f. fig. 6 of Michałowski et al. 2017).

In our sample of 119 sources, 26 (22 per cent) have no counterpart in any of the three Herschel bands to at least a 3σ level. This is in good agreement with the results of Michałowski et al. (2017). The mean $F_{850}$ for these sources with no counterpart is 5.3 ± 1.1 mJy. To examine the likely redshifts of these sources, we simulate at what redshifts we could reasonably expect to detect a 250, 350, or 500 μm Herschel detection by simulating the FIR flux using the single dust temperature MBB function

$$ S_ν ∝ \left(\frac{ν}{ν_0}\right)^β B_ν(T), $$

(1)

typically used to model FIR SEDs (Kelly et al. 2012). Here $\left(\frac{ν}{ν_0}\right)^β$ is the opacity of the dust, $ν_0$ is the characteristic frequency at which the dust becomes optically thick, $β$ is the dust emissivity and $B_ν(T)$ is the Planck function at temperature $T$. We assume a dust temperature of 40 K and two assumptions for the dust optical depth: a source with an optical depth that approaches 1 at 10 μm and a source with an optical depth that approaches 1 at 100 μm. We then fixed the 850 μm flux to the mean flux in our sample of unidentified sources and our results are shown in Fig. 14. We find that, if these sources are at $z < 2$, we would reasonably expect to detect them, at least in the 250 μm band. As we do not detect any SPIRE flux from these sources, it is difficult to constrain their properties much further, but Fig. 14 indicates that our average SPIRE-dropout is at least consistent with being a population of low luminosity SMGs at $z = 2$.

If we relax our constraint that the mean uncertainty be less than 1.6 mJy, we can search for rarer objects by increasing the area we are examining. In JINGLE101, we detect a background source to a 4.3σ level, with a 850 μm flux of 18.9 ± 4.9 mJy. This source is not detected in the 450 μm maps, nor is it detected to a significant level in the Herschel 250, 350 or 500 μm maps. At best, it is detected to a 2.6σ level in the 500 μm map, with a flux of 12.0 ± 4.7 mJy. Repeating the above blackbody simulation for this source suggests that, if its true 850 μm flux is 18.9 mJy, we would expect to detect it in the 500 μm band out to at least $z = 5.5$, assuming a dust temperature of 40 K and the source being optically thick at 100 μm. Assuming an optical depth of 1 at 1 μm, we should expect to detect this source out to $z = 7$. The nature of this Herschel dropout is uncertain: it could be a higher redshift analogue of the 500 μm risers ($F_{250} < F_{350} < F_{500}$), typically the highest redshift SMGs discovered by Herschel, or it could be part of a lower redshift but cooler population of SMGs, with dust temperatures below those of typical dusty star-forming galaxies at redshifts. However, the uncertainty on this source is somewhat large, and in fact lies outside of our initial selection limit of 3 mJy. We have been allocated ALMA time at 2 mm to further constrain the nature of this and several other bright 850 μm risers in the JINGLE fields, the results of which will be presented in a future paper.

6 CONCLUSIONS

We have introduced JINGLE, an ongoing large programme at the James Clerk Maxwell Telescope, and its MDR. The survey is designed to systematically study the cold ISM of galaxies in the local Universe. Over the period of 2015–2019, and making use of 780 h of observing time on the JCMT, JINGLE will provide integrated 850 μm continuum measurements with SCUBA-2 for a representative sample of 193 Herschel-selected galaxies, as well as CO(2–1) line fluxes and spectra with RxA3m for a subset of 90 of these galaxies. The galaxies in the sample have redshifts $0.01 < z < 0.05$ and stellar masses in the range $10^9$–$10^{11.5}$ M⊙. They are selected in SDSS from four fields chosen for having Herschel H-ATLAS imaging as well as coverage by the MaNGA and SAMI integral field optical spectroscopy surveys and upcoming large area blind H1 synthesis surveys.

The JCM observations will allow for the robust characterization of the dust properties (e.g. temperature, emissivity, grain properties) as well as the measurement of total molecular gas masses for the RxA3m subsample. The combination of all these datasets will allow a detailed characterization of the gas and dust properties and of the kinematics and metal contents of these galaxies, the derivation of scaling relations between dust, gas, and global properties, as well as provide critical benchmarks for high-redshift studies with JCMT and ALMA.
The MDR includes the SCUBA-2 observations for all 193 JINGLE galaxies, and RxA3m CO(2–1) line measurements for a subset of 63 of these. In addition, we have produced and release here a 30-band matched-aperture multiwavelength catalogue, including fluxes from GALEX FUV up to Herschel 500 μm. This catalogue is used to measure accurate and homogeneous stellar masses, star formation rates, and total infrared luminosities to be used alongside the JCMT data products.

Based on the 63 MDR galaxies with observations of both the CO(2–1) line and the 850 μm continuum, we show how low-mass galaxies ($M_* < 10^{10} M_\odot$) steepen the slope of the relation between $L_{CO}$ and $L_{850}$ and increase its scatter. By also quantifying how the properties of dust vary across the galaxy population, one of the aims of the survey is to calibrate how such relations can be used to infer the cold gas mass of galaxies with low metallicities and/or at high redshifts. In the three other papers accompanying this data release, we present in detail the RxA3m and SCUBA-2 observations as well as the catalogues of CO(2–1) line fluxes and sub-millimetre continuum measurements, and present some of the first scaling relations between dust properties and global galaxy properties.

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Herschel is an ESA space observatory with science instruments provided by European-led Principal Investigator consortia and with important participation from NASA. The Herschel spacecraft was designed, built, tested, and launched under a contract to ESA managed by the Herschel Planck Project team by an industrial consortium under the overall responsibility of the prime contractor Thales Alenia Space (Cannes), and including Astrium (Friedrichshafen) responsible for the payload module and for system testing at spacecraft level, Thales Alenia Space (Turin) responsible for the service module, and Astrium (Toulouse) responsible for the telescope, with in excess of a hundred subcontractors.

REFERENCES


\[\text{http://skyview.gsfc.nasa.gov/current/cgi/query.pl.}\]
SUPPORTING INFORMATION

Supplementary data are available at MNRAS online.

Table 2. Properties of the JINGLE galaxies.

Figure A3.

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APPENDIX A: SPECTRAL ENERGY DISTRIBUTIONS

We present for each of the 193 galaxies in the JINGLE sample the spectral energy distributions obtained from the CAAPR photometric catalogue (see Section 3.1 for details). Figs A1, A2 and A3 show examples of these SEDs, with the rest available as supplementary material. Each SED is accompanied by the best-fitting models obtained with MAGPHYS, and with the templates of Chary & Elbaz (2001) and Mullaney et al. (2011). Details of the modelling and of these specific templates are given in Section 3.2.
Figure A1. For each JINGLE galaxy, left: SDSS image, 1 arcmin × 1 arcmin, right: full SED from CAAPR as well as the MAGPHYS model (grey line) and modelling of the FIR SED using the templates of CE01 (red line) and JRM (blue line). These SEDs, and the fits to them, do not include the JCMT measurements.
Figure A2. Continued from Fig. A1.
Figure A3. Continued from Fig. A1. The remaining 10 pages of this figure are available online.
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