We present a new measurement of the evolving far-IR galaxy luminosity function (FLF) extending out to redshifts \(z > 5\), with resulting implications for the level of dust-obsured star-formation rate density in the young Universe. To achieve this, we have exploited an extensive sample of \(z > 5\) sub-mm galaxies imaged on SCUBA-2 on the James Clerk Maxwell Telescope (JCMT) and the Atacama Large Millimeter/Submillimeter Array (ALMA), which together provide unconstrained imaging with different dynamic ranges to provide unambiguous coverage of the luminosity-redshift plane out to \(z > 4\). Our results support previous indications that the faint-end slope of the far-IR LF is sufficiently flat that the faint-end luminosity-density is determined by high-redshift surveys. However, we find that the number-density/luminosity of such sources at high redshift has been severely over-estimated by studies that have attempted to push the highly-confused Herschel SPIRE surveys beyond \(z \approx 3\). Consequently we confirm recent reports that cosmic star-formation density is dominated by UV-visible star-formation at \(z > 4\), using both direct (1\(z\)\text{max}) and maximum likelihood determinations of the LF, we find that its high-redshift evolution is well characterized by continued positive luminosity evolution coupled with negative density evolution (with increasing redshift). This explains why bright sub-mm sources continue to be found at \(z > 5\), even through their integrated contribution to cosmic star-formation density at such early times is very small. The evolution of the far-IR galaxy LF thus appears similar in form to already established for active galactic nuclei, possibly reflecting a similar dependence on the growth of galaxy mass.

We used the data collected as a part of the SCUBA-2 Cosmology Legacy Survey (SCLS, Geach et al. 2017). The fields studied here are the UKIDSS-UDS, where the 850-\(\mu\)m imaging covers \(0.9\) deg\(^2\) with a total of \(90\) sources with a signal-to-noise ratio \(SNR > 3.5\), and the COSMOS field, where the 850-\(\mu\)m imaging covers \(1.3\) deg\(^2\) with the 10 noise of 16 mJy revealing 719 sources with \(SNR > 3.5\). To help affirm the measurement of the faint-end slope of the LF, we used the ALMA 1.3-mm imaging of the HUDF undertaken by Dunlop et al. (2017). A mosaic of 45 ALMA pointings was created to cover the full \(4.5\) arcmin\(^2\) area previously imaged with WFC3/IR on the HST. The ALMA map reached a noise level of \(\sigma = 35\) mJy beam\(^{-1}\), and 16 sources were detected with flux densities \(S > 120\) mJy. In addition, various ancillary data from UV to radio was utilised.

Because of the beam size of the JCMT/SCUBA-2 imaging at 850 \(\mu\)m (FWHM \(\sim 15\) arcsec), to identify optical counterparts we used the method described in Blain et al. (2003), where we adopt a 2.50 beam size radius around the SCUBA-2 position based on the signal-to-noise ratio \(SNR\). \(\sigma = 2.5\) \(\times 0.6\) \(FWHM\). Within this limit we identify the brightest source that is a given counterpart could have been selected by chance. Three imaging wavebands were used when searching for galaxy counterparts: the VLA 1.4-GHz imaging, the Spitzer MIPS 24-\(\mu\)m imaging, and the Spitzer IRAC 8-\(\mu\)m imaging. Once the counterparts were found in each of these bands, they were matched with the optical/near-IR catalogues using a search radius of \(r = 1.5\) arcsec and the closest object taken to be the galaxy counterpart. We used the available multi-wavelength data to derive the optical/near-IR photometric redshifts with a code based on the HYPHERZ package (Bolzonella et al. 2000), with the stellar population synthesis models of Bruzual & Charlot (2003), with the Chabrier (2003) stellar initial mass function (IMF), with Calzetti et al. (2000) dust attenuation law. The final redshift distributions are shown in Figure 1.

![Figure 1](image1.png)

**FIGURE 1.** The redshift distributions of the refined SCUBA-2 source sample used in this work. The black histogram depicts the distribution for all the sources, and [red] a mass-redshift of \(z > 2.73\) is shown. From the top, the colour plane shows the COSMOS deep, COSMOS wide and the UDS redshift distribution with a 2.50 arcmin and a 25 arcmin respectively.

To derive the evolving far-IR LF, we use two independent methods. One is the standard 1/V\(\nu\) method (Blain et al. 1998), where we have used a set of Schechter functions. In order to find the continuous form of the integral of the FLF, we have additionally used the maximum-likelihood (ML) method presented in Marshall et al. (1983).

For the 1/V\(\nu\) method, the LF in a given luminosity and redshift bin is calculated using the formula:

\[
\Phi (L, z) = \frac{1}{\Delta L} \int dL \int dz \Phi (L, z) F (\Delta L, z)
\]

where \(\Delta L\) is the width of the luminosity bin, \(F\) is the false detection rate, \(w_s\) is the completeness for the \(i\)-th galaxy and \(\Delta V\) is the comoving volume available to the \(i\)-th source. For SCLS sources the false detection rate is from (Geach et al. 2017).

The likelihood function used here (Marshall et al. 1983) is defined as a product of the probabilities of observing exactly one source in \(dL\), at all the position of the \(i\)-th galaxy \(z_i\) for \(N\) galaxies in our sample and of the probabilities of ob- serving zero sources in all the other differential elements in the luminosity-redshift plane. Using Poisson probabilities, the likelihood is:

\[
\mathcal{L} = \prod_i \left( \frac{\Phi(z_i)}{\mu(z_i)} \right) \left( \frac{1}{\mu(z_i)} \right)^{N-1} e^{-\Phi(z_i)}
\]

where \(\mu\) is the expected number of galaxies in \(dL\), \(N\) is the number of sources that were observed, and \(\Phi(z_i)\) is the luminosity density.

We have used the evolving far-IR LF derived here (with its combination of rising-then-falling characteristic density and positive evolution of characteristic luminosity-density with redshift), to predict the decline in both these quantities, but it can be seen that the continued positive evolution of \(L^*\) means that the most luminous sources persist, or indeed are preferentially found at the highest redshifts explored here.

To better connect with observables, we have used our evolving LF to calculate the predicted redshift distribution of \(850\mu m\) sources as a function of flux density. The results are shown for four different flux-density thresholds in the right panel of Figure 4. Here it can be seen that the peak in the redshift distribution is expected to naturally increase gradually from \(z < 1.8\) for \(85\%\) to \(z > 3\) for \(85\%\) to \(85\%\). This is in excellent accord with what has been reported in the literature (e.g. Kneib et al. 2014; Michalowski et al. 2016) and clarifies why, although dust-enshrouded star-formation is globally less important than UV-visible star-formation activity at \(z > 4\), bright sub-mm sources will continue to be discovered out to high redshifts.

Finally, we show here the form of the LF evolution uncovered here naturally explains the apparent ‘down- slope’ of the luminosity function at high redshift. In all statistical studies, evidence for such a decline is expected to naturally increase gradually from \(z < 1.8\) for \(85\%\) to \(z > 3\) for \(85\%\) to \(85\%\). This is in excellent accord with what has been reported in the literature (e.g. Kneib et al. 2014; Michalowski et al. 2016) and clarifies why, although dust-enshrouded star-formation is globally less important than UV-visible star-formation activity at \(z > 4\), bright sub-mm sources will continue to be discovered out to high redshifts.

We have utilised our measurement of the evolving IR LF to derive comoving IR luminosity density, and hence obscured SFRD, which we then combine with UV-estimates of unobscured activity (from Parsa et al. 2016), to derive the evolution of total SFRD. Consistent with several other recent studies (e.g. Bourne et al. 2017; Lacey et al. 2017), we find that SFRD declines beyond \(z > 2.5\) and is dominated by UV-visible star-formation activity above \(z > 4\).

Finally, we show how the evolution of the IR LF derived here (with its combination of rising-then-falling characteristic density \(\Phi^*\), and positive evolution of characteristic luminosity-density \(L^*\) with redshift), produces a decline in inferred SFRD beyond \(z > 2.5\) while at the same time predicting that the minimum redshift of sub-mm sources should increase with increasing flux density, consistent with several reports in the recent literature.

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