TRACING INFRARED GALAXIES THROUGHOUT COSMIC TIME

A DISSERTATION SUBMITTED TO THE GRADUATE DIVISION OF THE UNIVERSITY OF HAWAI’I IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

IN

ASTRONOMY

August 2015

By
Nicholas Y. Lee

Dissertation Committee:

David Sanders, Chairperson
Guenther Hasinger
Lisa Kewley
Emeric Le Floc’h
Kim Binsted
We certify that we have read this dissertation and that, in our opinion, it is satisfactory in scope and quality as a dissertation for the degree of Doctor of Philosophy in Astronomy.

DISSERTATION COMMITTEE

________________________
Chairperson

________________________
________________________
________________________

ii
Acknowledgements

I wish to thank my thesis advisor David Sanders for all of his help, advice, and scientific discussions throughout the course of my thesis work. Also thanks to my full thesis committee for reading and providing comments for this dissertation work.

I would also like to thank the various collaborators I have had the pleasure of working with, especially IfA post-docs Emeric Le Floc’h, Caitlin Casey, and Ezequiel Treister, who helped advise and teach me throughout my graduate studies. I also greatly appreciate my many conversations and work with other IfA graduate students, especially the ones that came together and formed the extragalactic journal club.

Finally, I would like to thank all of my family and friends who are always ready and able to provide much needed support and encouragement.
Abstract

Infrared observations are crucial for a full understanding of galaxy formation and evolution, as they reveal the full luminosity of galaxies enshrouded by ubiquitous interstellar dust. Ultraviolet and optical radiation from young massive stars is absorbed by dust grains that heat up and reradiate the absorbed radiation at far-infrared wavelengths. A complete characterization of the galactic emission requires observations at infrared wavelengths.

Using the recently launched *Herschel Space Telescope*, we analyze the deepest and most complete far-infrared surveys to characterize the dust-obscured star formation at high redshifts ($z \sim 0.5-3$). We provide the first detailed characterization of the full spectral energy distribution of infrared luminous galaxies at high redshift. By calibrating SFR indicators using far-infrared derived values, we extend our analysis to the full population of star-forming galaxies and discover new star formation laws that have important implications for galaxy evolution.
# Table of Contents

Acknowledgements ......................................................... iv
Abstract ................................................................. v
List of Tables .......................................................... viii
List of Figures ........................................................... ix
Chapter 1: Background ..................................................... 1
  1.1 Introduction ....................................................... 1
  1.2 Dust ............................................................... 2
  1.3 ULIRGs ............................................................ 3
  1.4 Star formation Laws ............................................... 5
  1.5 Summary .......................................................... 6
Chapter 2: A Far-IR Characterization of 24 μm Selected Galaxies at 0 < z < 2.5 using Stacking at 70 μm and 160 μm in the COSMOS Field ................. 11
  2.1 Abstract .......................................................... 11
  2.2 Introduction ...................................................... 12
  2.3 Data ............................................................... 14
    2.3.1 24 μm Catalog ............................................... 14
    2.3.2 70 μm and 160 μm Mosaics ................................ 15
    2.3.3 Photometric Redshifts ...................................... 15
  2.4 Analysis ........................................................ 16
    2.4.1 Stacking Methodology ...................................... 16
### 2.4.2 Uncertainties in Stacking

2.5 Results

2.5.1 Average 70 \( \mu m \) and 160 \( \mu m \) Flux Densities

2.5.2 Evolution of 70/24 \( \mu m \) and 160/24 \( \mu m \) Color with 24 \( \mu m \) Flux

2.6 Discussion

2.6.1 Comparison to Models

2.6.2 Best Fit Model SEDs and Average Total IR Luminosity

2.7 Summary

### Chapter 3: Multi-wavelength SEDs of Herschel Selected Galaxies in the COSMOS Field

3.1 Abstract

3.2 Introduction

3.3 Data and Sample Selection

3.3.1 Far-Infrared Observations

3.3.2 Observations at Shorter Wavelengths

3.3.3 Photometric Redshifts

3.3.4 Herschel Sample Selection

3.4 Dust Properties

3.5 Median SEDs

3.5.1 Constructing Median SEDs

3.5.2 Median SEDs as a Function of \( L_{IR} \)

3.5.3 Trends with Redshift or Luminosity?

3.6 Discussion

3.6.1 Stellar Mass and Star Formation Rate

3.6.2 Mid-Infrared to Far-Infrared Diagnostics

3.7 Conclusions

3.8 Acknowledgements

### Chapter 4: A Turnover in the Galaxy Main Sequence of Star Formation at \( M_* \sim 10^{10} M_\odot \) for Redshifts \( z < 1.3 \)
4.1 Abstract ................................................................. 74
4.2 Introduction .......................................................... 75
4.3 Data ................................................................. 77
  4.3.1 Source Selection ............................................... 78
  4.3.2 Infrared Data .................................................. 79
  4.3.3 Photometric Redshifts and Physical Parameters .......... 79
4.4 Analysis .......................................................... 80
  4.4.1 Star Formation Rate Calculations ........................... 80
  4.4.2 Comparison of SFR indicators ............................... 82
4.5 Shape of the Main Sequence of Star Formation ............... 87
  4.5.1 Parameterizing the Star-Forming Main Sequence .......... 90
  4.5.2 Evolution of Model Parameters ............................... 91
  4.5.3 Separating Quiescent Galaxies ............................... 93
4.6 Discussion .......................................................... 96
  4.6.1 The Turnover in the Star-Forming Main Sequence ........ 96
  4.6.2 Increasing SFR with Redshift ................................. 99
4.7 Conclusions ....................................................... 100
4.8 Acknowledgements ................................................ 101
Chapter 5: Summary and Future Work .............................. 108
  5.1 Summary .......................................................... 108
  5.2 Future Work - AGN in Infrared Galaxies ...................... 109
  5.3 Future Work - Quenching ......................................... 111
List of Tables

2.1 Number of sources in each redshift and $S_{24}$ bin . . . . . . . . . . . . . . . . . . . 17
2.2 Average 70 $\mu$m Flux Densities [mJy] and errors . . . . . . . . . . . . . . . . . . . 20
2.3 Average 160 $\mu$m Flux Densities [mJy] and errors . . . . . . . . . . . . . . . . . . . 20
2.4 Average $L_{\text{IR}} = L(8 - 1000\mu m)$ in [log $L_{\odot}$] . . . . . . . . . . . . . . . . 28
3.1 Average Properties of Herschel-selected galaxies . . . . . . . . . . . . . . . . . . . 56
4.1 Average Properties of Herschel-selected galaxies . . . . . . . . . . . . . . . . . . . 91
List of Figures

1.1 Evolution of the comoving IR energy density up to $z = 1$ (green), split into contributions from low-luminosity galaxies ($L_{\text{IR}} < 10^{11} L_\odot$; blue), LIRGs ($L_{\text{IR}} \geq 10^{11} L_\odot$; orange), and ULIRGs ($L_{\text{IR}} \geq 10^{12} L_\odot$; red), from Figure 14 in Le Floc’h et al. (2005). .......................... 4

2.1 Examples of a clean detection at 70 $\mu$m and a bad detection at 70 $\mu$m. The bad detection has a source in the center that does not resemble a clean point source, yet aperture photometry of this source yields a signal-to-noise of $\sim 14$. The circles in the lower left hand corners are the size of the aperture used to measure our stacked fluxes. .......................... 21

2.2 Stacked $S_{70}/S_{24}$ (top) and $S_{160}/S_{24}$ (bottom) flux ratios plotted as a function of $S_{24}$. Each color corresponds to a specific redshift bin, with bluer colors for low redshift and redder colors for high redshift bins. "Non-detections" are marked as upper limits, and 1-$\sigma$ error bars are plotted for the rest of the bins. 23

2.3 Fraction of sources in each bin that are also detected in the X-ray by XMM-Newton. At low $S_{24}$ bins, X-ray sources account for a very small fraction of our sources, but at high flux and high redshift bins the X-ray sources begin to account for a large fraction of sources. .......................... 24
2.4 Stacked $S_{70}/S_{24}$ and $S_{160}/S_{24}$ flux ratios compared to models of “normal” star-forming galaxies from DALE (black lines) [note: other empirical models cover a similar range] and models of Arp 220 (dark green line) and Mrk 231 (pink line) from SWIRE. The DALE models are a one parameter family of models, and we use the full range of DALE models, spanning $1 < \alpha < 2.5$. The model with the lowest $\alpha$, and also the lowest $L_{\text{IR}}$, is designated by the dot-dash line. Each colored dot represents a different $S_{24}$ bin, with dimmer sources at the blue end of the spectrum and brighter sources represented by redder colors. We see that our stacked colors are consistent with those of the DALE galaxies and Mrk 231, but not with Arp 220.

2.5 The ratio of $L_{\text{IR}}$ derived from only using $S_{24}$ vs. $L_{\text{IR}}$ derived from our stacking analysis. There is fairly good agreement between the two methods at low redshifts, but at higher redshifts we see that previous methods using only 24 $\mu$m flux overestimate the true luminosity, especially in the brighter 24 $\mu$m flux bins.

2.6a SED fits to stacked fluxes in each $S_{24}$ bin at a redshift $0 \leq z \leq 0.4$. The region spanned by the best-fit SEDs from each library is shaded. Non-detections are marked as upper limits, and the errors on the rest of the points are smaller than the size of the dot. Libraries used are from Dale & Helou (solid line), Chary & Elbaz (dotted line), Lagache et al. (dashed line), and Siebenmorgen & Krügel (dash-dot line).

2.6b SED fits to stacked fluxes in each $S_{24}$ bin at a redshift $0.4 \leq z \leq 0.6$. The region spanned by the best-fit SEDs from each library is shaded. Non-detections are marked as upper limits, and the errors on the rest of the points are smaller than the size of the dot. Libraries used are from Dale & Helou (solid line), Chary & Elbaz (dotted line), Lagache et al. (dashed line), and Siebenmorgen & Krügel (dash-dot line).
2.6c SED fits to stacked fluxes in each $S_{24}$ bin at a redshift $0.6 \leq z \leq 0.8$.

The region spanned by the best-fit SEDs from each library is shaded. Non-detections are marked as upper limits, and the errors on the rest of the points are smaller than the size of the dot. Libraries used are from Dale & Helou (solid line), Chary & Elbaz (dotted line), Lagache et al. (dashed line), and Siebenmorgen & Krügel (dash-dot line).

2.6d SED fits to stacked fluxes in each $S_{24}$ bin at a redshift $0.8 \leq z \leq 1.0$.

The region spanned by the best-fit SEDs from each library is shaded. Non-detections are marked as upper limits, and the errors on the rest of the points are smaller than the size of the dot. Libraries used are from Dale & Helou (solid line), Chary & Elbaz (dotted line), Lagache et al. (dashed line), and Siebenmorgen & Krügel (dash-dot line).

2.6e SED fits to stacked fluxes in each $S_{24}$ bin at a redshift $1.0 \leq z \leq 1.2$.

The region spanned by the best-fit SEDs from each library is shaded. Non-detections are marked as upper limits, and the errors on the rest of the points are smaller than the size of the dot. Libraries used are from Dale & Helou (solid line), Chary & Elbaz (dotted line), Lagache et al. (dashed line), and Siebenmorgen & Krügel (dash-dot line).

2.6f SED fits to stacked fluxes in each $S_{24}$ bin at a redshift $1.2 \leq z \leq 1.6$.

The region spanned by the best-fit SEDs from each library is shaded. Non-detections are marked as upper limits, and the errors on the rest of the points are smaller than the size of the dot. Libraries used are from Dale & Helou (solid line), Chary & Elbaz (dotted line), Lagache et al. (dashed line), and Siebenmorgen & Krügel (dash-dot line).
2.6g SED fits to stacked fluxes in each $S_{24}$ bin at a redshift $1.6 \leq z \leq 2.0$. The region spanned by the best-fit SEDs from each library is shaded. Non-detections are marked as upper limits, and the errors on the rest of the points are smaller than the size of the dot. Libraries used are from Dale & Helou (solid line), Chary & Elbaz (dotted line), Lagache et al. (dashed line), and Siebenmorgen & Krügel (dash-dot line).

2.6h SED fits to stacked fluxes in each $S_{24}$ bin at a redshift $2.0 \leq z \leq 3.0$. The region spanned by the best-fit SEDs from each library is shaded. Non-detections are marked as upper limits, and the errors on the rest of the points are smaller than the size of the dot. Libraries used are from Dale & Helou (solid line), Chary & Elbaz (dotted line), Lagache et al. (dashed line), and Siebenmorgen & Krügel (dash-dot line).

3.1 Selection function from our criteria requiring at least two detections in the Herschel PACS & SPIRE bands. The lines represent the selection function at various redshifts. The measured peak wavelengths and infrared luminosities of our Herschel sample are over-plotted as colored dots, with each color corresponding to galaxies that are at similar redshifts to the lines. The white circles represent the median peak wavelengths of our sample, while the white stars represent the mean peak wavelengths from the Symeonidis et al. (2013) study of Herschel galaxies. Even though our selection function is slightly biased against cold dust temperature sources, we find that our sample of Herschel galaxies have slightly longer median peak wavelengths than the Symeonidis et al. (2013) study.
3.2 Histograms of both bolometric infrared luminosity (top) and redshift (bottom) of our sample of over 4000 Herschel galaxies selected in the COSMOS field, requiring at least two detections in the far-infrared Herschel PACS or SPIRE bands. We also plot the histograms of sources split into redshift bins and infrared luminosity bins. The luminosity bins are selected so that there are approximately equal numbers of sources in each bin.

3.3 A comparison of the total infrared luminosity ($L_{\text{IR}}$) derived from our greybody fits on the x-axis and the $L_{\text{IR}}$ derived from fits to template libraries from Chary & Elbaz (2001) on the y-axis. Different colored filled circles represent galaxies in different redshift ranges, spanning $0 < z < 3.5$, while white circles represent running median values of the distribution. Typical errors are displayed on the right side of the plot. The $L_{\text{IR}}$ values measured from the two methods agree well, with the largest offset at low redshifts/infrared luminosities, where the C12 greybody fits have systematically lower infrared luminosities (although still within the typical uncertainties).

3.4 Spectral Energy Distributions (SEDs) of all sources in our sample. The top left panel displays the SEDs of the full sample of galaxies, in units of $\nu L_{\nu}$, redshifted to rest frame wavelengths and normalized so that every galaxy has $L_{\text{IR}} = 10^{11}L_{\odot}$, colored by luminosity bin. The remaining plots display the SEDs of the galaxies in each infrared luminosity bin, normalized to the mean $L_{\text{IR}}$ in that bin (black points). Overplotted on each plot is the derived median SED that was calculated in each bin (colored points). Error bars for the median SEDs can be found in Figure 3.5.
3.5 Median SEDs from each infrared luminosity bin, all normalized to the average $L_{\text{IR}}$ of the galaxies in that particular bin. The median SEDs are the same as those shown in Figure 3.4. Error bars are computed by measuring the value $\sqrt{N}$ ranks above and below the median value, where $N$ is the number of sources in that particular bin. Vertical lines are plotted to aid the eye in comparing the SEDs.

3.6 Median SEDs from each infrared luminosity bin, all normalized so that $\nu L_{\nu}(1.6\mu m) = 6 \times 10^{10} L_\odot$. The factor that each SED was multiplied by (when compared to Figure 3.5) is shown on the right side of the plot. This plot emphasizes the differences in emission at both mid-infrared and far-infrared wavelengths between galaxies in different luminosity bins.

3.7 Stellar Mass vs. SFR of our entire Herschel sample, colored by redshift. Our redshift bins span $z < 0.5$ (purple), $0.5 < z < 1.5$ (blue), $1.5 < z < 2.5$ (yellow), and $2.5 < z < 3.0$ (red). Colored solid lines represent the “main-sequence” of galaxies at $z \sim 0$ (purple, Daddi et al. 2007), $z \sim 1$ (blue, Daddi et al. 2007), and $z \sim 2$ (yellow, Elbaz et al. 2007), and the horizontal dotted lines simply mark the star formation rates that correspond to the infrared luminosities of LIRGs, ULIRGs, and HyLIRGs.
3.8 The effects of SED template choice on correction factors when calculating \( L_8 = \nu L_\nu(8\mu m) \). The different colors correspond to different templates that were used: Arp 220 (red), Mrk 231 (orange) and M82 (green) from the SWIRE template library (Polletta et al. 2007), mid-IR composite spectra from 13 SMGs from Pope et al. (2008, blue), and mid-IR composite spectra from starburst galaxies from Brandl et al. (2006, purple). The value plotted \((S_8/S_8(z = 2))\), gives the ratio of the correction factor applied at the desired redshift to the factor applied at a redshift of \( z = 2 \) (notice that every line crosses unity at \( z = 2 \)). We compare to \( z = 2 \) because we have \( 24\mu m \) observations for each source, and at \( z = 2 \), the \( 24\mu m \) directly probes rest frame \( 8\mu m \) and so has limited correction factors anyway (slight corrections are needed to account for the different passbands in MIPS \( 24\mu m \) and IRAC \( 8\mu m \)). For redshifts below \( z = 1 \), we calculate corrections using the observed IRAC \( 8\mu m \) flux densities, while at all other redshifts we use the MIPS \( 24\mu m \) flux densities. This plot displays the dangers in assuming a single “star-forming” SED template to calculate \( L_8 \), as the template you choose can drastically affect the inferred luminosities.

3.9 Top. A plot comparing \( L_{IR} \) and \( L_8 \) for our Herschel COSMOS sources, with each symbol colored by redshift. The dashed line represents the relationship quoted in E11. We see that the majority of our detected sources fall off the E11 relationship, in general having much higher \( L_{IR} \) than expected from the E11 relationship. Bottom. A plot detailing how IR8 \((\equiv L_{IR}/L_8)\) changes with infrared luminosity, with colored dots representing the same sources as in the top plot. A running median of IR8 in bins of \( L_{IR} \) is displayed with white circles. The black solid line represents the IR8 main-sequence defined by E11, with upper and lower limits drawn as black dotted lines. The maroon horizontal line represents the lower bound for galaxies deemed as “starburst” from their IR8. Typical uncertainties are plotted in the upper left hand corner.
4.1 Comparison of total SFR determined from combining direct measurements of FIR (Herschel, Lee et al. 2013) and UV (GALEX, Zamojski et al. 2007) with various SFR indicators using observations at shorter wavelengths. The different SFR indicators are: [top left] Spitzer 24 µm (Le Floc’h et al. 2009) + GALEX; [top right] multi-wavelength SED fits (Ilbert et al. 2013); [bottom left] NRK (0 < z < 1.3, Arnouts et al. 2013); and [bottom right] BzK (1.4 < z < 2.5, Daddi et al. 2007). In each panel, black contours give the density and concentration of sources, with extreme outliers plotted as gray circles. We bin the data in 20 equally populated bins (except BzK, which has 8 bins) and find the median $SFR_{\text{indicator}}$ in each bin. Errors on the median points are measured using a bootstrapping technique and are plotted when larger than the size of the symbol. At the top of each panel is the Pearson correlation coefficient (with a value of +1 indicating strong positive correlation and 0 indicating no correlation) and the typical difference between each particular SFR indicator and the Herschel-derived SFR.

4.2 Median difference in SFR estimated from infrared vs. optical/UV indicators, as a function of Total SFR. Sources that were detected by both SFR indicators were split in 15 equally populated $SFR_{\text{Total}}$ bins, and the median value is plotted, with error bars representing bootstrapped errors. We see that all indicators begin to deviate significantly at $log(SFR) \gtrsim 1.5$. (Top) Comparison of Spitzer 24 µm + GALEX (blue), multi-wavelength SED fits (green), NRK (orange, 0 < z < 1.3), and BzK (red, 1.4 < z < 2.5) to total SFR as derived from Herschel. (Bottom) Comparison of multi-wavelength SED fits (green), NRK (orange, 0 < z < 1.3), and BzK (red, 1.4 < z < 2.5) to total SFR as derived from Spitzer 24 µm.
4.3 Relative fraction of sources with SFRs determined from NRK (dotted line), Spitzer 24 μm (dashed line), and Herschel (solid line). Different colored lines represent percentages in different redshift bins, with bluer colors representing low redshifts and redder colors representing high redshifts.

4.4 Contour density plot of star-forming galaxies in the COSMOS field. We remove all galaxies classified as “quiescent” (unless they were detected in the infrared) and combine all star-forming galaxies, regardless of the specific SFR indicator used. To display the density of sources in the SFR/M* plane, each redshift slice was made into a grid of 51 × 51 bins, and the number of sources in each bin was calculated. Black contours show the density of galaxies, with contour levels set at 1/2 of the standard deviation of the number of sources in each bin. Colored vertical bars represent the median SFR in mass bins of width 0.3 dex and display the overall trend of the SFR/M* relationship. Histograms of matching color display the distribution of SFR in each mass bin along the sides of each plot. Main-sequence relationships from Karim et al. (2011, green dots) and Whitaker et al. (2014, blue line) are plotted for comparison.

4.5 Median SFR in 6 equally populated redshift bins that have been split into 30 equally populated stellar mass bins. Errors on the median are calculated from bootstrapping. Solid lines represent the best-fit curve to the model $S = S_0 - \log \left[ 1 + \left( \frac{10^M}{10^{M_0}} \right)^{-\gamma} \right]$. Vertical dashed line represents the stellar mass limit below which NRK has not been well-calibrated.
4.6 **Top:** Redshift evolution of the best-fit parameter values for (A) maximum of $\log(SFR)$, $S_0$; (B) turnover mass, $M_0$; and (C) power-law slope, $\gamma$. Different color dots represent parameter values in different redshift bins with 1-$\sigma$ error bars, and the dotted line is the best-fit linear fit to the data. **Bottom:** 95% confidence error ellipses displaying the covariance between (D) $S_0$ and $M_0$; (E) $S_0$ and $\gamma$; and (F) $\gamma$ and $M_0$, with different colors once again representing different redshift bins. We see moderate covariance in $\gamma$ and $M_0$, but little covariance between the other pairs.

4.7 $NUV - r^+$ vs. $r^+ - J$ plot of a mass-selected sample of galaxies in COSMOS at $0.2 < z < 1.3$. Black contours represent the full sample of galaxies, while orange circles highlight galaxies that are IR-detected, either with Herschel or Spitzer 24 $\mu$m. The red line, from I13, divides the sample into “star-forming” and “quiescent” galaxies. The majority of IR-detected galaxies are properly classified as “star-forming”, but there is a significant population ($\sim 7\%$) that are misclassified as “quiescent”.

5.1 Hardness ratio of stacked sources based on Chandra observations of the central square degree of COSMOS. Bins with $\geq 2\sigma$ detections in both soft and hard bands are represented by filled circles, colored by the $L_{\text{IR}}$ range of the bin. Bands without significant detections are assigned $2\sigma$ upper limits, and the hardness ratios are plotted as downward arrows. We see a slight trend of galaxies moving from M82-like hardness ratios to Mrk273-like hardness ratios as redshift and infrared luminosity are increased, but more data is needed to fill in the many bands without significant detections. Results from stacking Chandra emission from optically selected galaxies from Cowie et al. (2012) are shown as brown squares. We see that our infrared luminous galaxies generally have a harder X-ray spectrum than optical galaxies at the same redshift.
Chapter 1

Background

1.1 Introduction

Surveys of the sky at infrared wavelengths are crucial for studies of galaxy formation and evolution. Ubiquitous interstellar dust in galaxies absorbs the ultra-violet (UV) radiation from young, massive stars and reradiates thermally in the infrared. Thus, infrared observations provide us with a direct probe of the dust obscured radiation that is missed by observations at optical or UV wavelengths, where young, massive stars emit the majority of their radiation.

Dust obscuration happens to some degree in all galaxies, but is especially significant in the most bolometrically luminous galaxies where the total infrared radiation \( L_{\text{IR}} \equiv L(8-1000 \, \mu\text{m}) \) can dominate the galaxy’s overall luminosity (Sanders & Mirabel 1996). Although rare locally, these Luminous Infrared Galaxies (LIRGs, \( 10^{11}L_\odot < L_{\text{IR}} < 10^{12}L_\odot \)) and Ultra-Luminous Infrared Galaxies (ULIRGs, \( L_{\text{IR}} > 10^{12}L_\odot \)) have a significant contribution to the buildup of stellar mass and growth of supermassive black holes at higher redshifts, producing as much as 50% of the stellar mass in the universe at redshifts \( z \sim 2-3 \) (Chapman et al. 2005; Le Floc’h et al. 2005; Casey et al. 2012) and as much as \( \sim 30\% \) of the integrated black hole growth through highly obscured accretion (Treister et al. 2009, 2010).
In the following, I will discuss work done to use new infrared observations to properly account for dust obscuration in star-forming galaxies. In the rest of Chapter 1, I provide more detailed background and historical context for this work. Chapter 2, Chapter 3, and Chapter 4 describe work I have done in the study of infrared galaxies and star-formation at high redshifts. Chapter 5 summarizes our work and describes some of the future work inspired by our results.

1.2 Dust

Interstellar dust plays a key role in the star formation process. Dust is the dominant site for molecular hydrogen formation, as hydrogen atoms on the surface of dust grains can remain in proximity with each other long enough for radiative decay to the H\(_2\) molecules necessary for star formation. In addition, dust helps shield molecular clouds from dissociative UV radiation and far-infrared thermal radiation from dust removes gravitational energy from collapsing clouds.

While dust plays a major role in the star formation process, it also obscures a significant fraction of the luminosity produced by the young stellar population. Through absorption and scattering, small dust grains obscure and redden radiation, especially at UV wavelengths where the dust absorption cross section peaks and where young stars emit the bulk of their emission. The presence of dust is necessary for star-formation, but also serves as a major source of uncertainty in our ability to characterize the young stellar population that is commonly used as a tracer of a galaxy’s instantaneous star formation rate (SFR).

Fortunately, the absorbed radiation can be recovered by observations in (far)-infrared wavelengths. The absorbing dust grains in a galaxy are heated to typical dust temperatures \(T_D \sim 15\text{–}30\ \text{K}\) (Dunne et al. 2011; Dale et al. 2012; Auld et al. 2013) and thermally reradiate the absorbed radiation at infrared wavelengths, with a blackbody peak wavelength \(\sim 100\mu\text{m}\). Because the absorption cross section of interstellar dust is strongly peaked in
the UV, far-infrared emission can be a sensitive tracer of the young stellar population and instantaneous SFR.

### 1.3 ULIRGs

Early surveys of the sky at infrared wavelengths, first in 1983 with the *Infrared Astronomical Satellite* (IRAS) and later confirmed in surveys by the *Infrared Space Observatory* (ISO) and *Spitzer Space Telescope*, found that the most luminous galaxies \( L \gtrsim 10^{11} L_\odot \) in the local Universe \( (z \lesssim 0.3) \) were dominated by their infrared emission (Soifer et al. 1987; Kim & Sanders 1998; Sanders et al. 2003). This new class of “infrared luminous galaxies” emit more energy at infrared wavelengths than at all other wavelengths combined, and many of them were too faint to be included in previous optical catalogs.

These early studies demonstrated that many LIRGs \( (L_{\text{IR}} \gtrsim 10^{11} L_\odot) \) and all ULIRGs \( (L_{\text{IR}} \gtrsim 10^{12} L_\odot) \) in the local universe are powered by dust-enshrouded major mergers of gas-rich disk galaxies that drive nuclear inflow of gas and produce intense bursts of star-formation and fuel black hole accretion (see review by Sanders & Mirabel 1996).

Although rare locally, LIRGs and ULIRGs are much more numerous in the early universe (Figure 1.1; Le Floc’h et al. 2005) and have a significant contribution to the buildup of stellar mass and growth of supermassive black holes at higher redshifts, producing as much as 50% of the stellar mass in the universe at redshifts \( z \sim 2–3 \) (Chapman et al. 2005; Le Floc’h et al. 2005; Casey et al. 2012) and as much as \( \sim 30\% \) of the integrated black hole growth through highly obscured accretion (Treister et al. 2009, 2010).

Unfortunately, detailed studies of the more numerous, but more distant, high redshift population of infrared luminous galaxies has been severely hampered by instrument limitations. At redshifts \( z \sim 0.5–3 \), where the number density of (U)LIRGs increases by more than 2 orders of magnitude, flux and surface brightness dimming make it difficult to detect infrared galaxies and study their multi-wavelength counterparts (e.g. Hung et al. 2014).
Figure 1.1 Evolution of the comoving IR energy density up to $z = 1$ (green), split into contributions from low-luminosity galaxies ($L_{\text{IR}} < 10^{11}L_\odot$; blue), LIRGs ($L_{\text{IR}} \geq 10^{11}L_\odot$; orange), and ULIRGs ($L_{\text{IR}} \geq 10^{12}L_\odot$; red), from Figure 14 in Le Floc'h et al. (2005).

In addition, observations of high redshift galaxies trace radiation that is emitted at shorter rest-frame wavelengths. This is a problem because the deepest and highest resolution infrared observations have historically been in the near- and mid-IR (notably at 24 $\mu$m with Spitzer MIPS). In the local Universe, these mid-IR observations are sufficient for accurate estimates of the total infrared emission, but at higher redshifts the mid-IR observations trace shorter restframe wavelengths that no longer correlate as well with the far-IR luminosity (see Chapter 2; Papovich et al. 2007; Lee et al. 2010).

These challenges lead to our poor understanding of infrared luminous galaxies at high redshifts and demonstrate the need for improved observations at far-infrared wavelengths. The need for better characterization of obscured star-formation at $z \sim 1$–3 is further compounded by recent findings on the evolution of star-formation in galaxies that suggest
many “normal” star-forming galaxies at high redshift have elevated infrared luminosities that place them squarely in the regime of (U)LIRGs.

### 1.4 Star formation Laws

Recent studies suggest that at high redshifts \((z \sim 1–3)\), (U)LIRGs no longer consist of only the rare, bright tail of the galaxy population, but may encompass a significant fraction of star-forming galaxies. Specifically, the so-called “main-sequence of star-formation” (MS) is a well-studied relationship between galaxy star formation rate (SFR) and stellar mass \(\left(M_\ast\right)\) \citep{Noeske2007,Salim2007}. This relationship has three main properties:

- Galaxy star formation rates trace stellar mass as: \(SFR \propto M_\ast^\beta\), with \(\beta \sim 0.7–1.0\) \citep{Daddi2007,Elbaz2007}.

- The dispersion of this relationship is relatively constant, with \(\sigma \sim 0.3\) dex at all redshifts and stellar masses \citep{Speagle2014,Lee2015}.

- The normalization of the entire “main sequence” rises with redshift, scaling as \((1+z)^n\), with \(2.2 < n < 5\) \citep{Erb2006,Daddi2007,Damen2009,Dunne2009,Pannella2009,Karim2011}.

The rising normalization of the entire MS is of particular importance for studies of infrared luminous galaxies. Locally, the rare population of (U)LIRGs have very high SFRs and lie above the MS relationship. However, as the entire sequence rises, the general population of star-forming galaxies shifts into the regime of luminous infrared galaxies \((L_{\text{IR}} > 10^{11}L_\odot)\). The star-formation density of the Universe appears to peak precisely at these redshifts \citep{Madau1998,Bouwens2009}, highlighting the importance of a detailed understanding of what powers these high redshift luminous infrared galaxies.

Locally, detailed studies suggest that the only way for galaxies to produce the extreme luminosities seen in (U)LIRGs is through powerful mergers between two gas-rich galaxies, creating extreme starbursts that lie significantly off the “main sequence”, but this may not
be the case at high redshift. A common interpretation of the existence and tightness of the main-sequence is that the majority of star-forming galaxies are powered by similar quasi-steady processes, with only a small fraction of galaxies undergoing more chaotic processes such as major merger events that might be expected to produce strong bursts of star formation (e.g. Elbaz et al. 2011; Rodighiero et al. 2011; Sargent et al. 2012). Thus, it is thought that (U)LIRGs at high-redshift may instead simply be scaled up versions of the more “normal” star-forming galaxies seen locally, perhaps due to increased gas densities in the early universe.

However, recent studies suggest that the “main sequence” framework may not be as simple as originally presented. Some studies suggest that the MS slope varies with stellar mass so that a single power-law cannot explain the MS and a stellar mass-dependent slope is a better fit (Karim et al. 2011; Whitaker et al. 2012; Magnelli et al. 2014; Whitaker et al. 2014; Lee et al. 2015). Early studies based on far-infrared selected samples show that far-infrared selected galaxies lie mostly above the MS, with a much shallower slope in $\log(SFR)/\log(M_\ast)$ (Lee et al. 2013; Oteo et al. 2013a,b; Lemaux et al. 2013).

These discrepancies all point to the need for a detailed and complete study of high redshift star-forming galaxies at far-infrared wavelengths, where we can accurately characterize the effect dust absorption plays in studies of star formation.

1.5 Summary

Infrared luminous galaxies are some of the most luminous objects in the universe due to bursts of extreme star formation activity, but comprise only a small fraction of the local galaxy population. However, at higher redshifts where the star-formation history of the universe peaks, (U)LIRGs may instead be representative of the “typical” star-forming galaxy. Due to the massive amounts of dust shrouding these galaxies, observations at optical and/or UV wavelengths have difficulty probing the inner-workings of these systems. Instead,
we must rely on observations in the infrared, particularly at far-infrared wavelengths where we can probe the bulk of the restframe infrared luminosity.

The 2009 launch of the Herschel Space Observatory (Pilbratt et al. 2010) provided us with the first deep, large area surveys of the sky at 100–500 µm. One of the key deep fields surveyed with both the Photodetector Array Camera and Spectrometer (PACS: 100 µm, 160 µm; Poglitsch et al. 2010) and Spectral and Photometric Imaging Receiver (SPIRE, 250 µm, 350 µm, 500 µm; Griffin et al. 2010) instruments was the Cosmic Evolution Survey (COSMOS) field (Scoville et al. 2007), a 2 deg² field with extensive coverage in both multiwavelength imaging and spectroscopic observations. With this new and unique dataset, we can begin to examine what powers the extreme luminosities in infrared luminous galaxies at high redshift.

In the following dissertation, I describe my work studying infrared galaxies. Chapter 2 details the successes and shortcomings of using mid-IR observations as a probe of infrared luminosity, ultimately highlighting the need for deep surveys at far-infrared wavelengths for studies of high redshift galaxies. Chapter 3 provides a detailed analysis of the emission from the largest and most complete sample of infrared luminous galaxies detected by Herschel. Finally, in Chapter 4 I use new Herschel observations to calibrate an analysis of the full population of star-forming galaxies to gain insight on the physical nature of star formation in all galaxies. Chapter 5 provides a summary of our results and describes future work building off of these results.
References


Chapter 2

A Far-IR Characterization of 24 µm Selected
Galaxies at 0 < z < 2.5 using Stacking at 70 µm and
160 µm in the COSMOS Field


2.1 Abstract

We present a study of the average properties of luminous infrared galaxies detected directly at 24 µm in the COSMOS field using a median stacking analysis at 70 µm and 160 µm. Over 35,000 sources spanning 0 ≤ z ≤ 3 and 0.06 mJy ≤ S_{24} ≤ 3.0 mJy are stacked, divided into bins of both photometric redshift and 24 µm flux. We find no correlation of S_{70}/S_{24} flux density ratio with S_{24}, but find that galaxies with higher S_{24} have a lower S_{160}/S_{24} flux density ratio. These observed ratios suggest that 24 µm selected galaxies have warmer SEDs at higher mid-IR fluxes, and therefore have a possible higher fraction of AGN. Comparisons of the average S_{70}/S_{24} and S_{160}/S_{24} colors with various empirical templates and theoretical models show that the galaxies detected at 24 µm are consistent with “normal” star-forming galaxies and warm mid-IR galaxies such as Mrk 231, but inconsistent with heavily obscured galaxies such as Arp 220. We perform a χ² analysis to determine best fit galactic model
SEDs and total IR luminosities for each of our bins. We compare our results to previous methods of estimating $L_{\text{IR}}$ and find that previous methods show considerable agreement over the full redshift range, except for the brightest $S_{24}$ sources, where previous methods overpredict the bolometric IR luminosity at high redshift, most likely due to their warmer dust SED. We present a table that can be used as a more accurate and robust method for estimating bolometric infrared luminosity from 24 $\mu$m flux densities.

2.2 Introduction

Although rare in the present-day Universe, luminous infrared galaxies (LIRGs) were much more numerous in the past, and they may have played a significant role in the evolution of a large fraction of $L > L^*$ galaxies (Sanders & Mirabel 1996; Blain et al. 2002; Lagache et al. 2004; Le Floc’h et al. 2005). However, their exact contribution is still poorly understood due to two limitations that have plagued deep surveys performed so far: (i) the difficulty to identify the most obscured and distant of these objects, as well as measure their redshifts (they are often faint at optical wavelengths because of dust extinction, Houck et al. 2005), and (ii) the difficulty to accurately characterize their nature (bolometric luminosity, mass, physical processes powering their energy output). Furthermore, because of limited sensitivity of current space- (Spitzer MIPS) and ground-based (SCUBA, BOLOCAM, MAMBO, AzTEC,...) observations in the far-IR/submm, only a small number of the most luminous of these sources has been studied in detail. In addition, at high redshifts there are significant limitations due to confusion, which results from the very large instrument beam characterizing current far-IR/submm observations.

Many previous studies of luminous infrared galaxies have been based on data obtained with the Spitzer Space Telescope, in particular with the Multiband Imaging Photometer (MIPS, Rieke et al. 2004) at 24 $\mu$m, the detector’s most sensitive band. Using extrapolations based on libraries of galactic infrared (IR) spectral energy distributions (SEDs), the observed 24 $\mu$m flux is converted to a bolometric IR luminosity, $L_{\text{IR}} \equiv L(8\text{--}1000\mu\text{m})$, which is then
used to calculate properties such as instantaneous star formation rate (SFR). However, at higher redshifts the 24 µm band probes shorter rest frame wavelengths, probing rest frame 12 µm at $z \sim 1$, and rest frame 8 µm at $z \sim 2$. The typical peak of the IR SED of star forming galaxies and galaxies containing AGN falls around 50–200 µm; at higher redshifts, the 24 µm band probes wavelengths farther away from the peak of the IR SED and begins to be heavily affected by broad mid-infrared PAH emission and silicate absorption features.

Observations at longer wavelengths, such as in the Spitzer MIPS 70 µm and 160 µm bands (which probe rest frame 24 µm and 54 µm at $z \sim 2$, respectively), are needed to more accurately characterize the bolometric luminosity, especially at higher redshifts. However, the MIPS 70 µm and 160 µm bands are significantly less sensitive and have worse angular resolution than the 24 µm band. This leads to a drastic decrease in the number of sources directly detected at 70 µm and 160 µm, and the galaxies that are detected are biased toward the most luminous sources. Therefore, we use a stacking analysis (as in Dole et al. 2006; Papovich et al. 2007) to study the average 70 µm and 160 µm flux densities of galaxies detected at 24 µm. In using a stacking analysis we lose the ability to study individual galaxies, but find average properties of galaxies that would otherwise be undetectable.

In this work we explore the average mid- to far-IR flux densities of galaxies detected at 24 µm and derive a more accurate method to estimate bolometric IR luminosity. To accomplish this, we measure stacked 70 µm and 160 µm flux densities of galaxies detected at 24 µm in the COSMOS field, binned in both redshift and 24 µm flux. We use these stacked fluxes to examine the evolution of mid- to far-IR colors of galaxies as a function of luminosity and redshift. Our stacked fluxes are fit to libraries of galactic IR SED templates, from which we derive an estimate of the average bolometric IR luminosity. Papovich et al. (2007) carried out a similar study employing stacking at 70 µm and 160 µm, but their analysis was limited by area, with a significantly smaller number of sources. With an area almost ten times larger, we obtain more reliable statistics and the ability to bin our sources in narrower bins of redshift and flux. Our stacked fluxes will eventually be merged with
Herschel PACS (100 & 160 µm), Herschel SPIRE (200–500 µm), and SCUBA2 data to get the best sampled SEDs of the high-z literature.

Throughout this work we denote flux density, $f_\nu$ in MIPS 24 µm, 70 µm, and 160 µm bands as $S_{24}$, $S_{70}$, and $S_{160}$, respectively. When calculating rest-frame quantities, we use a cosmology with $\Omega_m = 0.3$, $\Lambda = 0.7$, and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$.

2.3 Data

We use data from the Cosmic Evolution Survey (COSMOS) field (Scoville et al. 2007), a $\sim 2$ deg$^2$ field centered at right ascension $10^{h}00^{m}28^{s}.6$, declination $02^{\circ}12'21''$ (J2000) with extensive multiwavelength imaging and spectroscopic coverage. In this study we make use of the COSMOS Spitzer (S-COSMOS, Sanders et al. 2007) observations, specifically the data taken by the Multiband Imaging Photometer in the 24 µm, 70 µm and 160 µm bands.

2.3.1 24 µm Catalog

The 24 µm data reduction and source extraction are detailed in Le Floc’h et al. (2009). The 24 µm sources were detected using the automatic procedure of the Sextractor software (Bertin & Arnouts 1996), and the flux densities were measured with multiple iterations of the Point Spread Function (PSF) fitting technique of the DAOPHOT package (Stetson 1987). Following the convention adopted by the Spitzer Science Center, a stellar 10,000 K black-body spectrum was assumed as the reference SED for the 24 µm flux density measurements.

The final source list is complete to more than 90% above a 24 µm flux of $S_{24} \sim 80\mu$Jy, and according to simulations, is still reliable down to fluxes as faint as 60 µJy, despite a lower completeness of 75%. The source list we use for our stacking analysis includes all sources with $S_{24} \geq 60\mu$Jy.
2.3.2 70 μm and 160 μm Mosaics

The MIPS 70 μm and 160 μm data were reduced and processed by Frayer et al. (2009). In short, the data was reduced using the Germanium Reprocessing Tools (GeRT, version 20060415) and additional specialized scripts developed for processing survey data from the MIPS-Germanium 70 μm and 160 μm detectors. The final 70 μm and 160 μm mosaics have an image pixel scale of 4″ and 8″ and point-source noise (1σ) of 1.7 mJy and 13 mJy, respectively, although there are local background fluctuations across the image depending on the local density of sources. Frayer et al. (2009) find 1512 sources at 70 μm, and 499 sources at 160 μm (≥ 5.0σ), but these detections represent the most luminous sources. In our stacking analysis, we do not treat these sources differently than 24 μm sources that were not detected at 70 μm and 160 μm (see Section 2.4).

2.3.3 Photometric Redshifts

The extensive multiwavelength coverage of the COSMOS field leads to photometric redshifts (hereafter photo-z) with an accuracy better than ever achieved in any other field, as detailed in Ilbert et al. (2009). Optical counterparts of the 24 μm sources were found from correlating the data with the K s−band COSMOS catalog of McCracken et al. (2010), as detailed in Le Floc’h et al. (2009). Photo-z were then calculated using fluxes in 30 bands, covering the far-UV at 1550 Å to the mid-IR at 8.0 μm. The uncertainties in the photo-z depend primarily on the redshift and apparent i + magnitude of the source, with errors increasing with fainter and more distant galaxies, but a comparison with faint spectroscopic samples in the COSMOS field revealed a dispersion as low as σ Δz/(1+z s) = 0.06 for sources with 23 mag< i AB < 25 mag at 1.5 ≲ z ≲ 3 (Lilly et al. 2007).

Approximately 1000 of our 24 μm sources are also detected in the X-ray by XMM-Newton (Brusa et al. 2010), and for these sources we use the photo-z’s derived from Salvato et al. (2009), who have the best photometric redshifts ever produced for AGN. In all, we have reliable photo-z for 35797 sources detected at 24 μm (~92% of the 38679 total 24 μm sources). We do not use the remaining sources without photo-z’s in our study, but these
sources are generally at the low $S_{24}$ end of our sample, where we have enough sources to perform a meaningful analysis.

2.4 Analysis

To study the average 70 $\mu$m and 160 $\mu$m properties of the IR luminous galaxies in the COSMOS field, we employ a median stacking analysis to overcome the poor sensitivity of the 70 $\mu$m and 160 $\mu$m MIPS detectors. Stacking of IR emission has proven valuable for studies such as average 24 $\mu$m fluxes in faint galaxies (Zheng et al. 2006) and contributions to the far IR extragalactic background (Dye et al. 2007). A stacking analysis of 70 $\mu$m and 160 $\mu$m fluxes of galaxies selected at 24 $\mu$m has been performed by Papovich et al. (2007). However, their analysis used data taken in the Extended Chandra Deep Field (ECDF-S), which covers 775 arcmin$^2$, and includes only 395 sources. As a result, they do not have significant detections in some of their lower 24 $\mu$m flux bins. With the COSMOS data, we have almost 100 times as many sources (stacking efficiency goes as $\sim N^{\frac{1}{2}}$), and will be able to make a much more detailed analysis with narrower bins in both redshift and rest-frame mid-IR luminosity.

We divide our 24 $\mu$m source list into bins of both redshift and $S_{24}$ before stacking. Redshift bins ensure that the fluxes we stack were emitted at the same rest-frame wavelength so that we probe the same parts of the SED, and $S_{24}$ bins separate galaxies with different IR luminosities. Our redshift and $S_{24}$ bins were chosen to maximize the number of sources in each bin while providing the best coverage in redshift and flux; Table 2.1 lists the bin limits and the corresponding number of sources in each bin.

2.4.1 Stacking Methodology

We begin by taking a $40 \times 40$ pixel ($2.7' \times 2.7'$ at 70 $\mu$m and $5.3' \times 5.3'$ at 160 $\mu$m) cutout centered around each 24 $\mu$m source in a given bin. For reference, the FWHM (Full Width Half Max) of the 70 $\mu$m mosaic is 18.6'' and the FWHM of the 160 $\mu$m mosaic is 39''. The
Table 2.1. Number of sources in each redshift and $S_{24}$ bin

<table>
<thead>
<tr>
<th>$S_{24}$ [mJy]</th>
<th>0–0.4</th>
<th>0.4–0.6</th>
<th>0.6–0.8</th>
<th>0.8–1.0</th>
<th>1.0–1.2</th>
<th>1.2–1.6</th>
<th>1.6–2</th>
<th>2–3</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.06–0.08</td>
<td>724</td>
<td>578</td>
<td>923</td>
<td>1281</td>
<td>1025</td>
<td>1573</td>
<td>1006</td>
<td>1002</td>
</tr>
<tr>
<td>0.08–0.10</td>
<td>501</td>
<td>423</td>
<td>701</td>
<td>887</td>
<td>688</td>
<td>1045</td>
<td>749</td>
<td>684</td>
</tr>
<tr>
<td>0.10–0.15</td>
<td>841</td>
<td>681</td>
<td>1011</td>
<td>1479</td>
<td>1092</td>
<td>1395</td>
<td>1280</td>
<td>896</td>
</tr>
<tr>
<td>0.15–0.20</td>
<td>528</td>
<td>421</td>
<td>588</td>
<td>834</td>
<td>535</td>
<td>557</td>
<td>629</td>
<td>482</td>
</tr>
<tr>
<td>0.20–0.50</td>
<td>1152</td>
<td>745</td>
<td>930</td>
<td>1354</td>
<td>628</td>
<td>597</td>
<td>790</td>
<td>604</td>
</tr>
<tr>
<td>0.50–1.00</td>
<td>408</td>
<td>153</td>
<td>136</td>
<td>187</td>
<td>61</td>
<td>75</td>
<td>73</td>
<td>78</td>
</tr>
<tr>
<td>1.00–3.00</td>
<td>228</td>
<td>35</td>
<td>28</td>
<td>26</td>
<td>11</td>
<td>21</td>
<td>20</td>
<td>21</td>
</tr>
</tbody>
</table>

size of the cutout does not affect the measured average (stacked) flux as long as the cutout encompasses a large enough area to make a local background estimate. We center each 70 µm and 160 µm subimage on the astrometric coordinates of the 24 µm source using a bilinear cubic interpolation, and then subtract a local background from each subimage; the local background is calculated from pixels exterior to $\sim 1'$ and $\sim 2'$ at 70 µm and 160 µm, respectively. Before creating our stacked image, we rotate each subimage by 90° with respect to the previous subimage to reduce the effects of image artifacts our analysis.

We then “stack” these subimages, aligned at the center (on-source) position and calculate a median flux density at each pixel position. A median stacking analysis is preferable to mean stacking because the median analysis is more stable and robust to small numbers of bright sources. The main problem with a mean stacking analysis is that it is very sensitive to bright outliers, which contaminate on-source flux measurements and introduce considerable noise from nearby, bright neighbors. Most mean stacking studies avoid this problem by removing bright sources from all images before stacking, but this technique solves one problem and creates two more. Removing bright sources introduces a slight bias against more luminous sources and the resultant stacked flux varies based on the exact flux density cutoff chosen; someone who chooses to remove all sources $\geq 4\sigma$ will measure a different flux than someone who chooses to remove all sources $\geq 3\sigma$. The
median stacking analysis avoids these problems, but is more difficult to interpret. From detailed comparisons of median and mean stacking, White et al. (2007) find that in “a limit where almost all the values in our sample are small compared with the noise . . . it is straightforward to interpret our median stack measurements as representative of the mean for the population of sources.” Our sample fits this description, with only $\sim 4\%$ of our sources detected at $70 \mu m$, and less than $2\%$ of our sources detected at $160 \mu m$, so we take the results of our median analysis as representative of the mean flux density.

We calculate the flux of our final stacked image using the DAOPHOT-type photometry IDL procedure, APER, with photometry aperture of $35''$ and sky annulus radii of $39''$–$65''$ at $70 \mu m$ (at $160 \mu m$, we use an aperture of $48''$ and sky radii of $64''$–$128''$). We use these radii in conjunction with the published MIPS aperture corrections for a $10 K$ blackbody given by the Spitzer Science Center (1.48 at $70 \mu m$ and 1.642 at $160 \mu m$) to estimate the total flux density from our stacked source.

### 2.4.2 Uncertainties in Stacking

We measure an error in our stacked flux densities from the variance in the local background of the stacked image and the uncertainty in the mean sky brightness. The absolute calibration of the MIPS detector at long wavelengths is $\sim 10\%$ (Gordon et al. 2007; Stansberry et al. 2007), and this dominates the errors in our stacked images in all but the noisiest of bins. Since a median analysis is a ranking measurement, we find an error in the median by sorting each pixel and then measuring the difference between the middle (median) value and the value that is $N^{1/2}$ ranks away from the middle, where $N^{1/2}$ is the Poissonian noise from a bin with $N$ sources. For all bins, this represents an almost negligible source of error.

To test for confusion from nearby bright sources, we searched the $24 \mu m$ catalog for nearby sources that would fall within the apertures used to measure the $70 \mu m$ and $160 \mu m$ flux densities. We find that only $\sim 3\%$ of our sources have a neighbor within the (larger) aperture used to measure the $160 \mu m$ flux. However, the location of each of
these nearby neighbors relative to the target source will not be uniform, which suggests that the contribution of nearby neighbors detected at 24 µm to our final stacked flux should be negligible. The fraction of galaxies with neighbors within the 160 µm aperture is fairly constant in all bins.

Confusion from faint sources can also add uncertainty to flux measurements; galaxy clustering suggests that the confusion from faint sources will generally be more significant near detected sources than at off-source background positions. The proper method to account for confusion from faint sources is still currently debated, but the uncertainty is expected to be important mostly for data at very long wavelengths, such as in the submillimeter regime, which is generally confusion-limited (H. Dole, private communication, 2010). The COSMOS MIPS data used in our stacking analysis is not confusion-limited, so we expect a negligible contribution from confusion.

2.5 Results

2.5.1 Average 70 µm and 160 µm Flux Densities

We performed a median stacking analysis for all 56 bins of redshift and S_{24} in our sample at both 70 µm and 160 µm. From a visual inspection of the images produced by the stacking analysis, we find clean detections in 88% of our 70 µm stacks, and 73% of our 160 µm stacks. The rest of the stacks can be split into two categories: (i) non-detections, which have no signal at all, and (ii) bad detections, which have a visible, but distorted signal that does not resemble a clean point spread function (PSF). The non-detections do not have enough signal-to-noise for an average source to emerge, but the bad detections don’t always have this same problem. The non-detections and bad detections are mostly in low flux and high redshift bins, although there are a few bad detections in the lowest flux bins with low/intermediate redshifts. The bins containing the non-detections and bad detections all have a fairly high number of sources, so we believe the lack of a clean detection is due simply to the faintness of the sources we are trying to stack. In the rest of our analysis, we
2.5.2 Evolution of 70/24

with in Papovich et al. (2007), who found an average \( \lesssim \) detection and a bad detection at 70\textmu m, with upper limits given for non-detections. Figure 2.1 displays an example of a clean detection and a bad detection at 70\textmu m.

Tables 2.2 and 2.3 list the measured 70\textmu m and 160\textmu m fluxes and errors in each of our bins, with upper limits given for non-detections. Figure 2.1 displays an example of a clean detection and a bad detection at 70\textmu m.

### Table 2.2. Average 70\textmu m Flux Densities [mJy] and errors

<table>
<thead>
<tr>
<th>( S_{24} ) [mJy]</th>
<th>0–0.4</th>
<th>0.4–0.6</th>
<th>0.6–0.8</th>
<th>0.8–1.0</th>
<th>1.0–1.2</th>
<th>1.2–1.6</th>
<th>1.6–2</th>
<th>2–3</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.06–0.08</td>
<td>1.65±0.18</td>
<td>0.60±0.09</td>
<td>0.64±0.09</td>
<td>0.63±0.08</td>
<td>0.73±0.10</td>
<td>0.77±0.09</td>
<td>&lt;0.18±0.06</td>
<td>&lt;0.01±0.07</td>
</tr>
<tr>
<td>0.08–0.10</td>
<td>1.81±0.20</td>
<td>1.82±0.20</td>
<td>1.42±0.16</td>
<td>0.94±0.12</td>
<td>1.23±0.15</td>
<td>1.17±0.13</td>
<td>0.32±0.08</td>
<td>&lt;0.19±0.08</td>
</tr>
<tr>
<td>0.10–0.15</td>
<td>2.49±0.26</td>
<td>2.37±0.25</td>
<td>1.36±0.15</td>
<td>1.23±0.13</td>
<td>1.41±0.15</td>
<td>1.33±0.14</td>
<td>0.45±0.07</td>
<td>0.43±0.07</td>
</tr>
<tr>
<td>0.15–0.20</td>
<td>2.13±0.23</td>
<td>3.21±0.34</td>
<td>2.26±0.24</td>
<td>2.23±0.23</td>
<td>1.88±0.20</td>
<td>1.79±0.20</td>
<td>1.00±0.13</td>
<td>0.85±0.12</td>
</tr>
<tr>
<td>0.20–0.50</td>
<td>4.85±0.49</td>
<td>4.91±0.50</td>
<td>4.13±0.42</td>
<td>2.95±0.30</td>
<td>3.21±0.33</td>
<td>3.12±0.32</td>
<td>1.29±0.15</td>
<td>1.48±0.17</td>
</tr>
<tr>
<td>0.50–1.00</td>
<td>11.42±1.15</td>
<td>11.49±1.16</td>
<td>8.50±0.85</td>
<td>6.41±0.66</td>
<td>6.00±0.65</td>
<td>3.45±0.41</td>
<td>4.66±0.51</td>
<td>4.17±0.47</td>
</tr>
<tr>
<td>1.00–3.00</td>
<td>24.35±2.44</td>
<td>19.39±1.97</td>
<td>17.80±1.82</td>
<td>9.40±1.60</td>
<td>15.93±1.68</td>
<td>5.68±0.68</td>
<td>10.01±1.11</td>
<td>6.28±0.72</td>
</tr>
</tbody>
</table>

### Table 2.3. Average 160\textmu m Flux Densities [mJy] and errors

<table>
<thead>
<tr>
<th>( S_{24} ) [mJy]</th>
<th>0–0.4</th>
<th>0.4–0.6</th>
<th>0.6–0.8</th>
<th>0.8–1.0</th>
<th>1.0–1.2</th>
<th>1.2–1.6</th>
<th>1.6–2</th>
<th>2–3</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.06–0.08</td>
<td>6.19±0.68</td>
<td>2.99±0.43</td>
<td>3.03±0.37</td>
<td>2.42±0.33</td>
<td>1.93±0.29</td>
<td>4.94±0.53</td>
<td>&lt;2.29±0.32</td>
<td>&lt;1.87±0.30</td>
</tr>
<tr>
<td>0.08–0.10</td>
<td>5.09±0.61</td>
<td>5.01±0.61</td>
<td>4.02±0.50</td>
<td>4.60±0.53</td>
<td>4.23±0.50</td>
<td>4.15±0.49</td>
<td>1.88±0.36</td>
<td>&lt;2.79±0.40</td>
</tr>
<tr>
<td>0.10–0.15</td>
<td>7.70±0.83</td>
<td>7.25±0.78</td>
<td>8.48±0.88</td>
<td>7.00±0.73</td>
<td>5.10±0.55</td>
<td>6.96±0.73</td>
<td>4.44±0.48</td>
<td>4.90±0.56</td>
</tr>
<tr>
<td>0.15–0.20</td>
<td>8.11±0.88</td>
<td>8.34±0.93</td>
<td>8.92±0.95</td>
<td>6.28±0.69</td>
<td>9.92±1.05</td>
<td>10.22±1.07</td>
<td>6.20±0.69</td>
<td>6.10±0.72</td>
</tr>
<tr>
<td>0.20–0.50</td>
<td>15.07±1.52</td>
<td>15.62±1.60</td>
<td>15.16±1.54</td>
<td>12.74±1.30</td>
<td>11.47±1.18</td>
<td>17.50±1.79</td>
<td>6.95±0.73</td>
<td>9.92±1.05</td>
</tr>
<tr>
<td>0.50–1.00</td>
<td>28.72±2.91</td>
<td>27.14±2.78</td>
<td>30.95±3.17</td>
<td>24.62±2.55</td>
<td>19.85±2.19</td>
<td>17.57±2.03</td>
<td>18.88±2.09</td>
<td>17.19±1.89</td>
</tr>
<tr>
<td>1.00–3.00</td>
<td>51.58±5.21</td>
<td>51.28±5.30</td>
<td>39.69±4.13</td>
<td>26.11±3.01</td>
<td>32.53±3.97</td>
<td>&lt;16.16±2.07</td>
<td>18.94±2.48</td>
<td>21.76±2.71</td>
</tr>
</tbody>
</table>

treat the non-detections as upper limits, but include the bad detections in our full analysis.

Tables 2.2 and 2.3 list the measured 70\textmu m and 160\textmu m fluxes and errors in each of our bins, with upper limits given for non-detections. Figure 2.1 displays an example of a clean detection and a bad detection at 70\textmu m.

2.5.2 Evolution of 70/24 \textmu m and 160/24 \textmu m Color with 24 \textmu m Flux

The mid- to far-infrared flux density ratios (or colors) of our stacked galaxies give us insight into the properties of the dust emission from these galaxies. Figure 2.2 shows the average stacked \( S_{70}/S_{24} \) and \( S_{160}/S_{24} \) flux ratios of our sources, with each color representing a different redshift bin. From the top panel of Figure 2.2, we see that the average \( S_{70}/S_{24} \) colors fall in the range \( 3 \lesssim S_{70}/S_{24} \lesssim 20 \), which is roughly consistent with results reported in Papovich et al. (2007), who found an average \( S_{70}/S_{24} \approx 9 \). They also find that sources with \( S_{24} > 250\textmu Jy \) have a lower average flux ratio (\( S_{70}/S_{24} \approx 5 \), but we do not see a trend
Figure 2.1 Examples of a clean detection at 70 \( \mu \)m and a bad detection at 70 \( \mu \)m. The bad detection has a source in the center that does not resemble a clean point source, yet aperture photometry of this source yields a signal-to-noise of \( \sim 14 \). The circles in the lower left hand corners are the size of the aperture used to measure our stacked fluxes.
of decreasing $S_{70}/S_{24}$ flux ratio with increasing $S_{24}$. Our results show a mostly flat $S_{70}/S_{24}$ color with respect to $S_{24}$.

We also find a trend of decreasing $S_{70}/S_{24}$ flux ratio with increasing redshift (from $S_{70}/S_{24} \approx 15$ at $z \sim 0.3$ to $S_{70}/S_{24} \approx 5$ at $z \sim 2$). This does not necessarily mean that high redshift galaxies have lower $S_{70}/S_{24}$ flux ratios because at higher redshifts, the observed $S_{70}/S_{24}$ measures flux ratios at shorter rest-frame wavelengths. Galaxies with strong mid-IR polycyclic aromatic hydrocarbon (PAH) features have mid-IR ($\sim 24\mu m$) emission that is flatter than their far-IR ($\sim 70\mu m$) emission, which will lead to a lower observed $S_{70}/S_{24}$ flux ratio at higher redshifts, even when observing galaxies with identical SEDs. We explore the dependence of $S_{70}/S_{24}$ on redshift further in Section 2.6.1 through comparisons of our stacking results with models.

Although we do not see a strong trend in $S_{70}/S_{24}$ ratio with $S_{24}$, we see a clear trend of decreasing $S_{160}/S_{24}$ ratio with increasing $S_{24}$ in the bottom panel of Figure 2.2. The average $S_{160}/S_{24}$ ratios we measure range from $10 \lesssim S_{160}/S_{24} \lesssim 100$ and are much larger than the $S_{70}/S_{24}$ ratios because the 160 $\mu m$ band samples fluxes emitted at wavelengths closer to the peak of galactic IR SEDs. Papovich et al. (2007) did not have high enough signal-to-noise in their stacks at 160 $\mu m$ to explore $S_{160}/S_{24}$ ratios, but they find average $S_{160}$ ranging from $3.8$ to $10.5$ mJy, broadly consistent with our values of $S_{160}$ in the lower $S_{24}$ bins.

Figure 2.2 shows that the brightest 24 $\mu m$ sources have low $S_{160}/S_{24}$ ratios. Given that $S_{24}$ broadly correlates with IR luminosity, this means that on average, more IR luminous galaxies have lower $S_{160}/S_{24}$ flux ratios, and therefore flatter spectrums. This trend is true in all our redshift bins, although the effect is less pronounced in our highest redshift bins.

The warmer $S_{160}/S_{24}$ colors in the higher $S_{24}$ bins suggest that these sources, on average, have a higher fraction of Active Galactic Nuclei (AGN) (Sanders & Mirabel 1996; Laurent et al. 2000). Dust grains in the dusty torus around AGN can be heated up to their sublimation temperature (1500 - 2000 K), while dust grains in the diffuse interstellar medium (ISM) and star-forming regions of galaxies are stochastically heated to lower temperatures.
Figure 2.2 Stacked $S_{70}/S_{24}$ (top) and $S_{160}/S_{24}$ (bottom) flux ratios plotted as a function of $S_{24}$. Each color corresponds to a specific redshift bin, with bluer colors for low redshift and redder colors for high redshift bins. “Non-detections” are marked as upper limits, and 1-σ error bars are plotted for the rest of the bins.
around 30 ∼ 40 K, or up to 200-400 K in HII regions. The emission from the warmer dust grains around AGN will mostly dominate in the mid-IR wavelengths, while the emission from the colder grains in star-forming regions will dominate the far-IR. Thus, galaxies powered by AGN will be flatter in their mid-IR to far-IR colors.

It should be noted that although we do find a trend of flatter $S_{160}/S_{24}$ ratios that is indicative of a higher fraction of AGN, our sources are still most likely dominated by star formation at the ∼85%–90% level (Le Floc’h et al. 2009). Out of our over 35000 sources, only ∼1000 have X-ray counterparts, suggesting that AGN make up a negligible population of our bins, except for possibly the highest $S_{24}$ bins. Figure 2.3 displays the fraction of sources in each bin that are also detected in the X-ray by XMM. At dim $S_{24}$ bins, we see that XMM sources indeed account for a low percentage of our sources. At bright $S_{24}$ bins, the X-ray detected sources begin to account for an appreciable fraction of our sources, but this does not mean that the mid- and far-IR fluxes of these sources are dominated by AGN. We discuss this further in Section 2.6.2.

![Figure 2.3 Fraction of sources in each bin that are also detected in the X-ray by XMM-Newton.](image)

Figure 2.3 Fraction of sources in each bin that are also detected in the X-ray by XMM-Newton. At low $S_{24}$ bins, X-ray sources account for a very small fraction of our sources, but at high flux and high redshift bins the X-ray sources begin to account for a large fraction of sources.
2.6 Discussion

2.6.1 Comparison to Models

In this section we compare the results of our stacking analysis with the expected fluxes and colors from theoretical models and empirical templates. We first compare our stacked $S_{70}/S_{24}$ and $S_{160}/S_{24}$ flux ratios with empirical models of “normal” star forming galaxies by Dale & Helou (2002, hereafter DALE) and models of Arp 220 and Mrk 231 from the SWIRE template library (Polletta et al. 2007). We then constrain the average IR luminosity for each bin by fitting to many libraries of theoretical models and empirical templates.

Figure 2.4 plots $S_{70}/S_{24}$ and $S_{160}/S_{24}$ color as a function of redshift, along with the expected values from the DALE models of star forming galaxies and the SWIRE models of Arp 220 and Mrk 231. The DALE models are a one parameter family of models and we show models that cover a range of $1 < \alpha < 2.5$, which describe normal star-forming galaxies with $8.3 < \log(L_{\text{IR}}) < 14.3$. Arp 220 is a well studied galaxy representative of heavily obscured ULIRGs, while Mrk 231 is representative of galaxies with warm mid-IR colors which are known to host AGN. We use the code Le Phare\(^1\) developed by S. Arnouts and O. Ilbert to determine the flux ratios of the DALE and SWIRE models at varying redshifts. Le Phare is a data analysis package used primarily to compute photometric redshifts, but a preliminary phase of the code also computes theoretical magnitudes, given SED libraries and filter bands. We can see immediately that the average colors determined from our stacking analysis fall within the region spanned by normal star-forming galaxies and Mrk 231, but our colors do not match those of Arp 220 at any redshift. This suggests that our 24 $\mu$m selection is biased against heavily obscured objects like Arp 220.

2.6.2 Best Fit Model SEDs and Average Total IR Luminosity

We use Le Phare to perform a $\chi^2$ analysis to find best fit galactic model SEDs for the stacked fluxes calculated in each bin. We use the empirical templates of Dale & Helou

\(^{1}\text{http://www.cfht.hawaii.edu/~arnouts/lephare.html}\)
Figure 2.4 Stacked $S_{70}/S_{24}$ and $S_{160}/S_{24}$ flux ratios compared to models of “normal” star-forming galaxies from DALE (black lines) [note: other empirical models cover a similar range] and models of Arp 220 (dark green line) and Mrk 231 (pink line) from SWIRE. The DALE models are a one parameter family of models, and we use the full range of DALE models, spanning $1 < \alpha < 2.5$. The model with the lowest $\alpha$, and also the lowest $L_{\text{IR}}$, is designated by the dot-dash line. Each colored dot represents a different $S_{24}$ bin, with dimmer sources at the blue end of the spectrum and brighter sources represented by redder colors. We see that our stacked colors are consistent with those of the DALE galaxies and Mrk 231, but not with Arp 220.
(2002), Lagache et al. (2003), Chary & Elbaz (2001), and the theoretical radiation pressure models of Siebenmorgen & Krügel (2007), finding the SED from each library that best fit our stacked data at the correct redshift. The average $S_{24}$, $S_{70}$, and $S_{160}$ in each bin are plotted along with the best fit models in Figure 2.6a–Figure 2.6h, arranged by redshift. Fluxes from the “non-detected” bins are shown as upper limits. The parameter space spanned by all four of the models is shaded to give an idea of the spread of possible SEDs that fit the data.

For our model fits, we use four different libraries of “normal” star-forming galaxies. We do have a small fraction of XMM detected sources that contain AGN, especially in the highest flux bins, but this does not imply that the mid-IR and/or far-IR fluxes of these galaxies is dominated by the AGN itself (many X-ray sources are PAH dominated in the infrared). Because of the small number of sources, we are unable to perform a separate stacking analysis of only these X-ray sources. Although we cannot account for the true contribution of AGN contamination, the tight fits we see suggest that most of our sources are indeed star formation dominated.

From the maximum likelihood function of the $\chi^2$ analysis, we estimate a median $L_{\text{IR}}$ and 1-$\sigma$ uncertainties in each bin of our stacking analysis. We repeat this measurement for each library separately, and then take the mean of the four $L_{\text{IR}}$ values to estimate the true luminosity. The dispersion of the luminosities derived from the different libraries is $\sim 6\% (3\sigma)$ in all our bins, which suggests that the four libraries are fairly consistent in their estimates of the best-fit $L_{\text{IR}}$. We add the 1-$\sigma$ uncertainties from each library in quadrature to estimate the error in $L_{\text{IR}}$, and find typical $3\sigma$ errors around 3\%. The average IR luminosities and errors measured for each of our bins is listed in Table 2.4. Bins classified as non-detections at both 70 µm and 160 µm are marked as upper limits. As expected, we see that total IR luminosity increases with $S_{24}$ and with redshift. These galaxies span a large range of IR luminosity, covering “normal” galaxies ($L_{\text{IR}} \leq 10^{11}L_\odot$), Luminous Infrared Galaxies (LIRGs, $10^{11}L_\odot \leq L_{\text{IR}} \leq 10^{12}L_\odot$), and Ultra Luminous Infrared Galaxies (ULIRGs, $L_{\text{IR}} \geq 10^{12}L_\odot$). To test our uncertainties, we also found best fit SEDs using
Table 2.4. Average $L_{IR} = L(8 – 1000 \mu m)$ in $[\log L_{\odot}]$

<table>
<thead>
<tr>
<th>Redshift Range</th>
<th>$S_{24}$ [mJy]</th>
<th>0.0–0.4 (0.3)</th>
<th>0.4–0.6 (0.5)</th>
<th>0.6–0.8 (0.7)</th>
<th>0.8–1.0 (0.9)</th>
<th>1.0–1.2 (1.1)</th>
<th>1.2–1.6 (1.4)</th>
<th>1.6–2 (1.8)</th>
<th>2–3 (2.3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.06–0.08</td>
<td>9.96±0.07</td>
<td>10.41±0.09</td>
<td>10.74±0.10</td>
<td>10.90±0.09</td>
<td>11.12±0.09</td>
<td>11.66±0.09</td>
<td>&lt;11.60±0.10</td>
<td>&lt;11.84±0.12</td>
<td></td>
</tr>
<tr>
<td>0.08–0.10</td>
<td>9.97±0.07</td>
<td>10.66±0.08</td>
<td>10.89±0.07</td>
<td>11.10±0.12</td>
<td>11.39±0.09</td>
<td>11.69±0.11</td>
<td>11.62±0.12</td>
<td>&lt;12.01±0.14</td>
<td></td>
</tr>
<tr>
<td>0.10–0.15</td>
<td>10.16±0.06</td>
<td>10.82±0.07</td>
<td>11.11±0.10</td>
<td>11.27±0.12</td>
<td>11.47±0.10</td>
<td>11.84±0.09</td>
<td>11.88±0.13</td>
<td>12.22±0.18</td>
<td></td>
</tr>
<tr>
<td>0.15–0.20</td>
<td>10.18±0.07</td>
<td>10.89±0.08</td>
<td>11.19±0.08</td>
<td>11.35±0.08</td>
<td>11.69±0.10</td>
<td>12.00±0.08</td>
<td>12.06±0.11</td>
<td>12.36±0.20</td>
<td></td>
</tr>
<tr>
<td>0.20–0.50</td>
<td>10.49±0.07</td>
<td>11.16±0.08</td>
<td>11.46±0.10</td>
<td>11.61±0.10</td>
<td>11.82±0.11</td>
<td>12.24±0.17</td>
<td>12.12±0.20</td>
<td>12.55±0.22</td>
<td></td>
</tr>
<tr>
<td>0.50–1.00</td>
<td>10.81±0.07</td>
<td>11.44±0.06</td>
<td>11.77±0.10</td>
<td>11.92±0.10</td>
<td>12.07±0.11</td>
<td>12.33±0.19</td>
<td>12.55±0.15</td>
<td>12.83±0.20</td>
<td></td>
</tr>
<tr>
<td>1.00–3.00</td>
<td>11.10±0.07</td>
<td>11.69±0.07</td>
<td>11.95±0.07</td>
<td>11.98±0.09</td>
<td>12.34±0.08</td>
<td>12.23±0.11</td>
<td>12.68±0.20</td>
<td>13.04±0.23</td>
<td></td>
</tr>
</tbody>
</table>

Note. — Average redshifts and $S_{24}$ for each bin are given in parentheses. Bins in which both 70 µm and 160 µm stacks resulted in non-detections are marked as upper limits.

70 µm and 160 µm flux densities that were offset by the errors given in Tables 2.2 & 2.3 and then measured $L_{IR}$ from these fits. We find discrepancies much less than 6% from this trial, suggesting that our derived infrared luminosities are robust within the errors in our stacking analysis.

Table 2.4 gives a relation between observed $S_{24}$ and total IR luminosity, with no need for a k-correction. This is an extremely valuable tool given the poor sensitivity of longer wavelength instruments, and provides an effective way to estimate $L_{IR}$ when only having 24 µm data. Some caution must be taken when using Table 2.4 to estimate $L_{IR}$. Although the agreement between the best fit models from many libraries is fairly robust, it is not a complete description of the errors. For most of these bins, we do not have data on the Rayleigh Jean side of our IR SEDs, which means we can not estimate the cold dust component and its contribution to $L_{IR}$. This means that Table 2.4 is valid under assumption that the libraries used are representative of the diversity of the SEDs beyond 160µm/(1+z). These results will be tested in the near future with Herschel and SCUBA2.

Figure 2.5 shows a comparison of $L_{IR}$ calculated from our stacking analysis and $L_{IR}$ calculated from extrapolating mid-IR fluxes from only $S_{24}$ based on the Dale SED libraries, as is common practice. In general, the two methods are in good agreement at low redshifts, but the $L_{IR}$ calculated using only 24 µm data is an overestimate of the true $L_{IR}$ at high
redshifts, especially for the brighter $S_{24}$ sources. This is most likely due to the warmer dust SEDs that we find in the bright $S_{24}$ sources (Section 2.5.2). Our results are consistent with the findings of Calzetti et al. (2007), who find that rest-frame 24 $\mu$m flux is a much better indicator of bolometric infrared luminosity than 8 $\mu$m flux, and with the findings of Papovich et al. (2007), who find that the $L_{\text{IR}}$ estimated without taking into account stacked 70 $\mu$m and 160 $\mu$m fluxes overestimates the true $L_{\text{IR}}$. To summarize, extrapolating a bolometric infrared luminosity from a 24 $\mu$m flux density without taking into account 70 $\mu$m and 160 $\mu$m flux will result in an overestimate of $L_{\text{IR}}$ at high redshifts. Table 2.4 will give a more accurate and robust estimate of $L_{\text{IR}}$ at these redshifts.

![Figure 2.5](image)

Figure 2.5 The ratio of $L_{\text{IR}}$ derived from only using $S_{24}$ vs. $L_{\text{IR}}$ derived from our stacking analysis. There is fairly good agreement between the two methods at low redshifts, but at higher redshifts we see that previous methods using only 24 $\mu$m flux overestimate the true luminosity, especially in the brighter 24 $\mu$m flux bins.
2.7 Summary

We perform a median stacking analysis on over 35000 sources detected directly at 24 µm in the COSMOS field at $0 \leq z \leq 3$ and $0.06 \text{ mJy} \leq S_{24} \leq 3.0 \text{ mJy}$ to study their average flux densities at 70 µm and 160 µm. Of the 56 bins used, 95% had detections at 70 µm and 93% had detections at 160 µm. Analysis of the $S_{70}/S_{24}$ and $S_{160}/S_{24}$ flux density ratios suggest:

- 24 µm sources have average flux-density ratios consistent with empirical models of “normal” star-forming galaxies or with warm mid IR galaxies, like Mrk 231, which are known to host AGN.

- 24 µm sources have average flux-density ratios that are inconsistent with Arp 220, which suggests that 24 µm is not very useful for finding heavily obscured objects like Arp 220.

- Sources with brighter $S_{24}$ have warmer $S_{160}/S_{24}$ flux ratios, decreasing by a factor of 2 from $0.1 \lesssim S_{24}/\text{mJy} \lesssim 1.0$, which implies that more IR luminous galaxies have a higher fraction of AGN.

Our stacking analysis provides the largest statistical study of the average far-IR flux densities of the faint 24 µm population. A comparison of the average far-IR fluxes to libraries of empirical templates and theoretical models allows us to estimate the total IR luminosity of a typical galaxy detected at 24 µm within certain redshift and $S_{24}$ bins. We find that previous studies based on extrapolating $L_{\text{IR}}$ from 24 µm data, without far-IR stacking, generally overpredict the total infrared luminosity, especially at higher redshifts. A more accurate method for estimating $L_{\text{IR}}$ using only 24 µm flux and redshift is provided in Table 2.4, which takes into account the average mid- and far-IR fluxes of 24 µm selected galaxies.
Figure 2.6a SED fits to stacked fluxes in each $S_{24}$ bin at a redshift $0 \leq z \leq 0.4$. The region spanned by the best-fit SEDs from each library is shaded. Non-detections are marked as upper limits, and the errors on the rest of the points are smaller than the size of the dot. Libraries used are from Dale & Helou (solid line), Chary & Elbaz (dotted line), Lagache et al. (dashed line), and Siebenmorgen & Krügel (dash-dot line).
Figure 2.6b SED fits to stacked fluxes in each $S_{24}$ bin at a redshift $0.4 \leq z \leq 0.6$. The region spanned by the best-fit SEDs from each library is shaded. Non-detections are marked as upper limits, and the errors on the rest of the points are smaller than the size of the dot. Libraries used are from Dale & Helou (solid line), Chary & Elbaz (dotted line), Lagache et al. (dashed line), and Siebenmorgen & Krügel (dash-dot line).
Figure 2.6c SED fits to stacked fluxes in each $S_{24}$ bin at a redshift $0.6 \leq z \leq 0.8$. The region spanned by the best-fit SEDs from each library is shaded. Non-detections are marked as upper limits, and the errors on the rest of the points are smaller than the size of the dot. Libraries used are from Dale & Helou (solid line), Chary & Elbaz (dotted line), Lagache et al. (dashed line), and Siebenmorgen & Krügel (dash-dot line).
Figure 2.6d SED fits to stacked fluxes in each $S_{24}$ bin at a redshift $0.8 \leq z \leq 1.0$. The region spanned by the best-fit SEDs from each library is shaded. Non-detections are marked as upper limits, and the errors on the rest of the points are smaller than the size of the dot. Libraries used are from Dale & Helou (solid line), Chary & Elbaz (dotted line), Lagache et al. (dashed line), and Siebenmorgen & Krügel (dash-dot line).
Figure 2.6e SED fits to stacked fluxes in each $S_{24}$ bin at a redshift $1.0 \leq z \leq 1.2$. The region spanned by the best-fit SEDs from each library is shaded. Non-detections are marked as upper limits, and the errors on the rest of the points are smaller than the size of the dot. Libraries used are from Dale & Helou (solid line), Chary & Elbaz (dotted line), Lagache et al. (dashed line), and Siebenmorgen & Krügel (dash-dot line).
Figure 2.6f SED fits to stacked fluxes in each $S_{24}$ bin at a redshift $1.2 \leq z \leq 1.6$. The region spanned by the best-fit SEDs from each library is shaded. Non-detections are marked as upper limits, and the errors on the rest of the points are smaller than the size of the dot. Libraries used are from Dale & Helou (solid line), Chary & Elbaz (dotted line), Lagache et al. (dashed line), and Siebenmorgen & Krügel (dash-dot line).
<Redshift> = 1.81

Figure 2.6g SED fits to stacked fluxes in each $S_{24}$ bin at a redshift $1.6 \leq z \leq 2.0$. The region spanned by the best-fit SEDs from each library is shaded. Non-detections are marked as upper limits, and the errors on the rest of the points are smaller than the size of the dot. Libraries used are from Dale & Helou (solid line), Chary & Elbaz (dotted line), Lagache et al. (dashed line), and Siebenmorgen & Krügel (dash-dot line).
Figure 2.6h SED fits to stacked fluxes in each $S_{24}$ bin at a redshift $2.0 \leq z \leq 3.0$. The region spanned by the best-fit SEDs from each library is shaded. Non-detections are marked as upper limits, and the errors on the rest of the points are smaller than the size of the dot. Libraries used are from Dale & Helou (solid line), Chary & Elbaz (dotted line), Lagache et al. (dashed line), and Siebenmorgen & Krügel (dash-dot line).
References


Chary, R., & Elbaz, D. 2001, ApJ, 556, 562 [(document), 2.6.2, 2.6a, 2.6b, 2.6c, 2.6d, 2.6f, 2.6g, 2.6h]

Dale, D. A., & Helou, G. 2002, ApJ, 576, 159 [(document), 2.6.1, 2.6.2, 2.6a, 2.6b, 2.6c, 2.6d, 2.6e, 2.6f, 2.6g, 2.6h]


Lagache, G., Dole, H., & Puget, J. 2003, MNRAS, 338, 555 [(document), 2.6.2, 2.6a, 2.6b, 2.6c, 2.6d, 2.6e, 2.6f, 2.6g, 2.6h]


Siebenmorgen, R., & Krügel, E. 2007, A&A, 461, 445 [(document), 2.6.2, 2.6a, 2.6b, 2.6c, 2.6d, 2.6e, 2.6f, 2.6g, 2.6h]


Chapter 3

Multi-wavelength SEDs of Herschel Selected Galaxies in the COSMOS Field


3.1 Abstract

We combine Herschel PACS and SPIRE maps of the full 2 deg$^2$ COSMOS field with existing multi-wavelength data to obtain template and model-independent optical-to-far-infrared spectral energy distributions (SEDs) for 4,218 Herschel-selected sources with log($L_{IR}/L_{\odot}$) = 9.4–13.6 and $z = 0.02–3.54$. Median SEDs are created by binning the optical to far-infrared (FIR) bands available in COSMOS as a function of infrared luminosity. Herschel probes rest-frame wavelengths where the bulk of the infrared radiation is emitted, allowing us to more accurately determine fundamental dust properties of our sample of infrared luminous galaxies. We find that the SED peak wavelength ($\lambda_{peak}$) decreases and the dust mass ($M_{dust}$) increases with increasing total infrared luminosity ($L_{IR}$). In the lowest infrared luminosity galaxies ($\log(L_{IR}/L_{\odot}) = 10.0–11.5$), we see evidence of Polycyclic Aromatic Hydrocarbons (PAH) features ($\lambda \sim 7–9$ $\mu$m), while in the highest infrared luminosity
galaxies ($L_{\text{IR}} > 10^{12} L_{\odot}$) we see an increasing contribution of hot dust and/or power-law emission, consistent with the presence of heating from an active galactic nucleus (AGN). We study the relationship between stellar mass and star formation rate of our sample of infrared luminous galaxies and find no evidence that Herschel-selected galaxies follow the $SFR/M_*$ “main sequence” as previously determined from studies of optically selected, star-forming galaxies. Finally, we compare the mid-infrared (MIR) to FIR properties of our infrared luminous galaxies using the previously defined diagnostic, $\text{IR8} \equiv L_{\text{IR}}/L_8$, and find that galaxies with $L_{\text{IR}} \gtrsim 10^{11.3} L_{\odot}$ tend to systematically lie above ($\times 3–5$) the IR8 “infrared main sequence”, suggesting either suppressed PAH emission or an increasing contribution from AGN heating.

3.2 Introduction

Surveys of the sky in far-infrared wavelengths are crucial to gain a complete understanding of the nature of extragalactic objects. Dust in galaxies absorbs the ultra-violet (UV) radiation from young, massive stars and reradiates thermally in the infrared. This happens to some degree in all galaxies, but in the most bolometrically luminous galaxies, the total infrared radiation ($L_{\text{IR}} \equiv L(8–1000 \ \mu\text{m})$) dominates the total emission (e.g. Sanders & Mirabel 1996). Although rare locally, these Luminous Infrared Galaxies (LIRGs, $10^{11} L_{\odot} < L_{\text{IR}} < 10^{12} L_{\odot}$) and Ultra-Luminous Infrared Galaxies (ULIRGs, $L_{\text{IR}} > 10^{12} L_{\odot}$) have a significant contribution to the buildup of stellar mass and growth of supermassive black holes at higher redshifts, producing as much as 50% of the stellar mass in the universe at redshifts $z \sim 2–3$ (Chapman et al. 2005; Le Floc’h et al. 2005; Casey et al. 2012) and as much as $\sim 30\%$ of the integrated black hole growth through highly obscured accretion (Treister et al. 2009, 2010).

The Herschel Space Observatory (Pilbratt et al. 2010) provides us with the first sensitive observations of the sky at far-infrared wavelengths, where the bulk of the infrared radiation is emitted. This allows us to more accurately measure bolometric infrared luminosity, which
is a fundamental property of galaxies and is thought to be an excellent tracer of the star formation rate in (U)LIRGs (e.g. Kennicutt 1998). One of the key deep fields surveyed with Herschel was the Cosmic Evolution Survey (COSMOS) field (Scoville et al. 2007), a 2 deg$^2$ field with extensive coverage of multiwavelength imaging and spectroscopic observations. With this new and unique dataset, we can begin to examine what powers the extreme luminosities in infrared luminous galaxies.

A major drawback of many previous studies of infrared luminous galaxies is that they do not have sufficient wavelength coverage at FIR wavelengths ($\sim 100 \, \mu$m), where the SED peaks. Many previous studies have relied on uncertain extrapolations from available wavebands (e.g. Spitzer 24$\mu$m) that can be affected by AGN contamination or poor assumptions of the SED shape in the FIR. This becomes especially problematic for studies at high redshift, as the available wavebands are redshifted even farther away from the FIR peak of the SED, and the MIR bands begin to be contaminated by PAH emission that can vary substantially in strength. In addition, many of the extrapolations are based on fits to SED libraries (e.g. Chary & Elbaz 2001; Dale & Helou 2002; Draine & Li 2007) that are constructed from galaxies at low redshift, and these models may not represent the SEDs of high redshift galaxies. Indeed, studies using stacking techniques to better study long wavelength data have shown that extrapolations from mid-IR wavelengths are generally accurate at low redshifts and low infrared luminosities, but become significantly less accurate at high redshifts and high infrared luminosities (Papovich et al. 2007; Lee et al. 2010; Kirkpatrick et al. 2012). Studies at submillimeter wavelengths ($\lambda \gtrsim 850 \mu$m) avoid the problem of extrapolation from MIR wavelengths, but are affected by a severe bias in dust temperature (Blain et al. 2004; Chapman et al. 2004; Casey et al. 2009).

In this paper, we select galaxies at wavelengths where their FIR SEDs peak, avoiding the need for uncertain extrapolations from MIR observations and avoiding the temperature bias of submillimeter surveys. We study the full SEDs (UV-to-FIR) of a large population of Herschel-selected galaxies without using any prior assumptions of SED shape.
This paper is organized as follows: the data are described in Section 4.3 and in Section 3.4 we examine the fundamental dust properties of our full sample of 4,218 galaxies. In Section 3.5, we construct median SEDs and investigate how they evolve as a function of $L_{\text{IR}}$. In Section 4.6, we discuss whether there is evidence that our objects lie on the optical and infrared “main-sequence” as suggested by previous studies of star-forming galaxies and infrared luminous galaxies. When calculating rest-frame quantities, we use a cosmology with $\Omega_m = 0.3$, $\Lambda = 0.7$, and $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and we also assume a Salpeter initial mass function (IMF: Salpeter 1955) when deriving SFRs and stellar masses.

### 3.3 Data and Sample Selection

#### 3.3.1 Far-Infrared Observations

We use observations from the *ESA Herschel Space Observatory* (Pilbratt et al. 2010), in particular employing *Herschel’s* large telescope and powerful science payload to do photometry using the Photodetector Array Camera and Spectrometer (PACS, Poglitsch et al. 2010) and Spectral and Photometric Imaging Receiver (SPIRE, Griffin et al. 2010) instruments.

The COSMOS field has been observed down to the confusion limit of $\sim 20\text{mJy}$ at 250$\mu$m, 350$\mu$m, and 500$\mu$m by *Herschel* SPIRE as part of the *Herschel* Multi-tiered Extragalactic Survey (HerMES; Oliver et al. 2012). In order to measure accurate flux densities of sources in the confusion-dominated SPIRE mosaics, we use the linear inversion technique of cross-identification (hereafter XID), as described in Roseboom et al. (2010, 2012). A linear inversion technique fits the flux density of all known sources simultaneously, but the accuracy of such a technique is greatly dependent on the completeness of the sample of prior known sources. For infrared sources, the list of priors is generally taken as sources that are bright at 24$\mu$m or 1.4 GHz. Observations at both of these wavelengths have much better resolution than FIR observations, and both are thought to correlate strongly with total infrared luminosity (Helou et al. 1985; Condon 1992; Kennicutt 1998; Rieke et al. 2009).
Our COSMOS-\textit{Spitzer} \citep{Sanders2007} survey provides very deep coverage at 24\,$\mu$m, containing $>$39,000 sources with $S_{24} > 80\mu$Jy (90\% completeness limit) over an effective area of 1.68 \, deg$^2$ \citep{LeFloc'h2009}, and complete coverage at 1.4 GHz with the VLA, leading to 2,865 sources with $1\sigma \sim 12\mu$Jy \citep{Schinnerer2010}. While we include 1.4 GHz counterparts when extracting sources from the SPIRE map to ensure completeness of our list of priors, we also require a 24\,$\mu$m counterpart for our SPIRE detections in order to maintain uniformity with the PACS sources. The XID method provides flux density measurements for every input source, but following the recommendations in \citet{Roseboom2010}, we only keep sources with $S/N > 5$ and $\chi^2 < 5$. This yields 8,308 sources detected at 250\,$\mu$m, 3,186 sources detected at 350\,$\mu$m, and 955 sources detected at 500\,$\mu$m, with typical 1\,$\sigma$ total noise (instrumental + confusion) of 2.2, 2.9, and 3.2 mJy in the 250, 350, and 500\,$\mu$m bands, similar to what was found in \citet{Roseboom2012}.

\textit{Herschel} PACS observations in the COSMOS field at 100\,$\mu$m and 160\,$\mu$m were performed as a part of the PACS Evolutionary Probe program (PEP; \citealt{Lutz2011}). Catalog extraction was performed blindly, using the Starfinder PSF-fitting code \citep{Diolaiti2000}, and employing 24\,$\mu$m priors following the method described in \citet{Magnelli2009}, but in this work we use the sources extracted from 24\,$\mu$m priors to maintain consistency with the SPIRE sources that are extracted using 24\,$\mu$m priors.

### 3.3.2 Observations at Shorter Wavelengths

Optical counterparts of our \textit{Herschel} sample are found following the matching algorithm adopted by \citet{LeFloc'h2009}. As a necessity of our \textit{Herschel} source extraction, all of our sources have 24\,$\mu$m counterparts. Thus, we first find $K_s$-band counterparts (from \citealt{McCracken2010}) for each 24\,$\mu$m source using a matching radius of 2". A matching radius of 1" is then used to match these $K_s$-band counterparts to the $i^+$-band selected photo-z catalog of \citet{Ilbert2009}. Sources without $K_s$-band counterparts are matched directly to the photo-z catalog using a matching radius of 2". The photo-z catalog contains Subaru B, V, $g+$, $r+$, $i+$, $z+$, \citep{Capak2007, Taniguchi2007} and Ultra-VISTA...
J, K (McCracken et al. 2012) fluxes, in addition to excellent photometric redshifts for 933,789 sources selected at $i^+_{AB} < 26.5$ mag from the Subaru/Suprime-CAM observations of COSMOS (Capak et al. 2007). Spitzer IRAC (Sanders et al. 2007) 3.6µm, 4.5µm, 5.8µm, and 8µm counterparts are found using a similar method, by matching to the $K_s$-band counterparts using a 1" matching radius. We also find sub-millimeter flux densities from AzTEC (Scott et al. 2008; Aretxaga et al. 2011) and MAMBO (Bertoldi et al. 2007) by using a matching radius of 2" for the sources that have radio counterparts. In all, we have full multi-wavelength coverage of Herschel-selected sources from optical through sub-millimeter wavelengths.

### 3.3.3 Photometric Redshifts

As mentioned in Section 3.3.2, the extensive multiwavelength coverage in the COSMOS field leads to extremely accurate photometric redshifts (hereafter photo-z), detailed in Ilbert et al. (2009). Photo-z are calculated using fluxes in 30 bands, covering the far-UV at 1550 Å to the mid-IR at 8.0µm. The uncertainties in the photo-z depend primarily on the redshift and apparent $i^+$ magnitude of the source, with errors increasing with fainter and more distant galaxies, but a comparison with faint spectroscopic samples in the COSMOS field revealed a dispersion as low as $\sigma_{\Delta z/(1+z_s)} = 0.06$ for sources with 23 mag < $i^+_{AB}$ < 25 mag at $1.5 \lesssim z \lesssim 3$ (Lilly et al. 2007). Casey et al. (2012) find that photo-z’s can be much less accurate for infrared-selected samples, with $\sigma_{\Delta z/(1+z_s)} \approx 0.3$ at $z < 2$, but there is no evidence of a systematic offset.

Approximately 1000 of our 24µm sources are also detected in the X-ray by XMM-Newton (Brusa et al. 2010) or Chandra (Civano et al. 2011), and for these sources we use the photo-z’s derived from Salvato et al. (2011), who have the best photometric redshifts ever produced for AGN, reaching $\sigma_{\Delta z/(1+z_s)} = 0.015$ for sources with $i^+_{AB} < 22.5$ out to $z = 4.5$. 

46
3.3.4 Herschel Sample Selection

We restrict our sample of Herschel-selected galaxies to sources with $\geq 5\sigma$ detections in at least two of the five Herschel PACS and SPIRE bands (100, 160, 250, 350, or 500µm). This requirement reduces the contamination from spurious detections and gives us enough data points in the far-infrared to accurately constrain the shape of the infrared SED (see Section 3.4). This selection ultimately results in 4,218 sources spanning redshifts $0.02 < z < 3.5$.

As with any selection, there are biases that affect our sample. The requirement of a 24µm source to use as a prior biases our sample against heavily obscured objects and high-redshift objects (Roseboom et al. 2010; Casey et al. 2012) or galaxies with strong silicate absorption features that are redshifted into the 24µm band (Magdis et al. 2011). The biases introduced by our requirement of $5\sigma$ detections in two of the five Herschel bands is less obvious. To explore the biases introduced by our selection criteria, we model the SEDs of galaxies spanning a wide range of peak wavelength ($\lambda_{\text{peak}} \sim 10$–$300$µm), infrared luminosity ($\log(L_{\text{IR}}/L_\odot) \sim 8$–14), and redshift ($z \sim 0$–3.5). We then convolve these (redshifted) model SEDs with the transmission curves of the relevant Spitzer and Herschel bands to determine their observed flux densities. Figure 3.1 displays the selection functions in peak wavelength and infrared luminosity space at different redshifts. At most redshifts, we see a slight bias against sources with long peak wavelengths (colder dust temperatures), although by requiring detections in multiple wavelengths, we see much flatter selection functions than typically seen in single-band selections.

3.4 Dust Properties

We estimate the total infrared luminosity ($L_{\text{IR}}$) of individual Herschel-selected galaxies by directly fitting their FIR photometry to a coupled modified greybody plus a MIR power law\(^1\), as in C12. The main strength of this technique is that we do not rely on templates which

\(^{1}\text{http://www.ifa.hawaii.edu/~cmcasey/sedfitting.html}\)
Figure 3.1 Selection function from our criteria requiring at least two detections in the *Herschel* PACS & SPIRE bands. The lines represent the selection function at various redshifts. The measured peak wavelengths and infrared luminosities of our *Herschel* sample are over-plotted as colored dots, with each color corresponding to galaxies that are at similar redshifts to the lines. The white circles represent the median peak wavelengths of our sample, while the white stars represent the mean peak wavelengths from the Symeonidis et al. (2013) study of *Herschel* galaxies. Even though our selection function is slightly biased against cold dust temperature sources, we find that our sample of *Herschel* galaxies have slightly longer median peak wavelengths than the Symeonidis et al. (2013) study.

incorporate a myriad of free parameters, most of which cannot realistically be constrained by data; instead, using this simple model, we can cleanly fit the available photometric data without introducing biases which are template-dependent.

C12 compare this greybody fitting technique with template fits from Chary & Elbaz (2001, hereafter CE01), Dale & Helou (2002), Draine & Li (2007) and Siebenmorgen & Krügel (2007) using local (U)LIRGs from the GOALS survey (Armus et al. 2009, U et al. 2012), and find that the simple greybody plus power-law fits provide a statistically better fit to the data than any of the templates at all wavelengths. One potential drawback of this simple fit is that it does not fit PAH features in the MIR, although such spectral features could be modeled on top of the simple fit in the future. However, the net contribution of
PAH features to the integrated 8–1000µm infrared luminosity is negligible (< 5%). Without detailed information in the MIR, fits to PAH features can be extremely uncertain.

As suggested in C12, we fix the MIR powerlaw slope, \( \alpha = 2.0 \), and the dust emissivity, \( \beta = 1.5 \). For each source we then perform the fit using all available photometric data at observed wavelengths \( \lambda \geq 24\mu m \). Our SED fits allow us to constrain \( L_{IR} \), peak wavelength (\( \lambda_{peak} \)), and dust mass (\( M_{dust} \)), with typical uncertainties of \( \sigma_{L_{IR}} \sim 0.15 \) dex, \( \sigma_{\lambda_{peak}} \sim 13\mu m \), and \( \sigma_{M_{dust}} \sim 0.38 \) dex. The rest-frame SED peak wavelength of \( S_{\nu} \) is a proxy for dust temperature (\( \lambda_{peak} \propto 1/T_{dust} \)), but the actual conversion to dust temperature is very dependent on the assumed opacity and emissivity model. For example, an SED that peaks at 100µm can have a dust temperature of 29°K (blackbody), 31°K (optically thin greybody), 44°K (greybody with \( \tau = 1 \) at 100µm), or 46°K (greybody with \( \tau = 1 \) at 200µm).

Due to these uncertainties in dust temperature from different model assumptions (see C12 for more details), we prefer to estimate \( \lambda_{peak} \), which is insensitive to model assumptions.

We plot \( \lambda_{peak} \) and \( L_{IR} \) for our entire sample in Figure 3.1 on top of the selection function for our sample. Symeonidis et al. (2013) previously analyzed the dust temperatures of a sample of Herschel-selected galaxies that is near-complete in SED types and is thought to be representative of the infrared galaxy population as a whole up to \( z \sim 2 \). We convert their measured mean dust temperatures to \( \lambda_{peak} \) and find good agreement between our two studies: both studies show similar trends in rest-frame peak wavelength vs. \( L_{IR} \), with nearly equal values at the highest infrared luminosities and slightly cooler values for our current study at lower infrared luminosities.

Our sample of Herschel-selected galaxies spans a range \( \log(L_{IR}/L_{\odot}) \approx 9.4–13.6 \), which we show in Figure 3.2. We then compare \( L_{IR} \) determined from our greybody & power-law fits to \( L_{IR} \) determined from fitting to SED templates from CE01 in Figure 3.3. We use the code Le Phare\(^2\) developed by S. Arnouts and O. Ilbert to fit the infrared SEDs to the models from CE01. Le Phare is a data analysis package used primarily to compute photometric redshifts, but can also be used to perform a \( \chi^2 \) analysis to find best fit galactic

\(^2\)http://www.cfht.hawaii.edu/~arnouts/lephare.html
model SEDs in the far-infrared. At low redshift (and low infrared luminosity), we see that the C12 greybody fits measure lower infrared luminosities than the CE01 template fits by an average of about 0.1 dex, similar to what was seen in C12 when they compared these two methods using the GOALS sample of local (U)LIRGs. Over the entire sample, the luminosities computed from each method differ by an average of $\sim 0.11$ dex, within the typical uncertainty in $L_{\text{IR}}$ of $\sim 0.15$ dex, with a slightly larger disagreement at high redshifts and high infrared luminosities. This is not surprising since all of our sources are detected in multiple Herschel bands and are fairly well constrained at FIR wavelengths.

3.5 Median SEDs

To examine detailed galaxy SEDs without making assumptions on the SED shape, we construct average SEDs that will allow us to study the average properties of a population of galaxies (e.g. Kirkpatrick et al. 2012). By combining galaxies at different redshifts, we also sample different rest-frame wavelengths, allowing us to sample a larger portion of the full SED without requiring observations in additional passbands. In this section, we describe our methodology for constructing median SEDs and then discuss what these SEDs tell us about the average properties of infrared luminous galaxies.

3.5.1 Constructing Median SEDs

An inherent assumption in any averaging technique is that all of the sources in a particular bin have similar SEDs. We restrict our averaging analysis to galaxies with similar emission properties by splitting our sample of Herschel-selected galaxies into bins based on their total infrared luminosity calculated from their individual SED fits. The implications of this binning are discussed in Section 3.5.3. We split our sample into five infrared luminosity bins to probe SED evolution with SFR: $\log(L_{\text{IR}}/L_\odot) = 10-10.99, 11-11.49, 11.5-11.99, 12-12.49, \text{and } 12.5-13.5$. Due to the dynamical range of this survey, these bins also coincide
Figure 3.2 Histograms of both bolometric infrared luminosity (top) and redshift (bottom) of our sample of over 4000 Herschel galaxies selected in the COSMOS field, requiring at least two detections in the far-infrared Herschel PACS or SPIRE bands. We also plot the histograms of sources split into redshift bins and infrared luminosity bins. The luminosity bins are selected so that there are approximately equal numbers of sources in each bin.

with different redshift bins, with the lowest luminosity sources at \( \langle z \rangle \sim 0.3 \) and the highest at \( \langle z \rangle \sim 2 \).

For each source, we combine all the available photometry in COSMOS, from Subaru B-band through Herschel-SPIRE 500\( \mu m \) for all sources (or up to \( \approx 1 \) mm for those sources detected with AzTEC and/or MAMBO). The SEDs for individual sources are redshifted to the object rest-frame wavelengths and converted to units of \( \nu L_\nu \) using photometric redshifts. In each luminosity bin, we then normalize all the SEDs so that each source has the same
Figure 3.3 A comparison of the total infrared luminosity ($L_{\text{IR}}$) derived from our greybody fits on the x-axis and the $L_{\text{IR}}$ derived from fits to template libraries from Chary & Elbaz (2001) on the y-axis. Different colored filled circles represent galaxies in different redshift ranges, spanning $0 < z < 3.5$, while white circles represent running median values of the distribution. Typical errors are displayed on the right side of the plot. The $L_{\text{IR}}$ values measured from the two methods agree well, with the largest offset at low redshifts/infrared luminosities, where the C12 greybody fits have systematically lower infrared luminosities (although still within the typical uncertainties).

infrared luminosity, which we set as the average $L_{\text{IR}}$ of all sources in that particular bin (see Table 4.1). Once all photometric points are properly redshifted and normalized, we bin the data into wavelength bins from 0.1 $\mu$m to 1000 $\mu$m, with a logarithmic width of 0.05 dex. We only include bins that have at least 20 data points and where the standard error of the mean ($\sigma/\sqrt{N}$) is smaller than 0.05. These limits are empirically chosen with the intent of having as much wavelength coverage as possible, but not including erroneous median values that were affected by small number statistics. Including median values of wavelength bins that don’t meet this criteria introduce large, unphysical variations that skew the SEDs. Figure 3.4 displays all of the normalized and rest-frame SEDs, with our calculated median SED over plotted. Error bars for each median point are calculated by measuring the value.
\( \sqrt{N} \) ranks away from the median value, where \( N \) is the number of sources in that particular bin.

Figure 3.4 Spectral Energy Distributions (SEDs) of all sources in our sample. The top left panel displays the SEDs of the full sample of galaxies, in units of \( \nu L_\nu \), redshifted to rest frame wavelengths and normalized so that every galaxy has \( L_{\text{IR}} = 10^{11} L_\odot \), colored by luminosity bin. The remaining plots display the SEDs of the galaxies in each infrared luminosity bin, normalized to the mean \( L_{\text{IR}} \) in that bin (black points). Overplotted on each plot is the derived median SED that was calculated in each bin (colored points). Error bars for the median SEDs can be found in Figure 3.5.
Figure 3.5 Median SEDs from each infrared luminosity bin, all normalized to the average $L_{\text{IR}}$ of the galaxies in that particular bin. The median SEDs are the same as those shown in Figure 3.4. Error bars are computed by measuring the value $\sqrt{N}$ ranks above and below the median value, where $N$ is the number of sources in that particular bin. Vertical lines are plotted to aid the eye in comparing the SEDs.

3.5.2 Median SEDs as a Function of $L_{\text{IR}}$

We plot all the median SEDs together in Figure 3.5 in order to directly compare the SEDs and see how the typical SED changes with $L_{\text{IR}}$. Since the photometry in each bin has been normalized to the median $L_{\text{IR}}$ in that bin, we see a very clear variation of the strength of the far-infrared emission in each median SED. Another clear trend is that the far-infrared SEDs peak at shorter wavelengths at higher $L_{\text{IR}}$, peaking at $\lambda \sim 100\mu\text{m}$ in the lowest luminosity bin and peaking at $\lambda \sim 60\mu\text{m}$ in the highest luminosity bin. Since the infrared SED is dominated by blackbody emission at these wavelengths, this suggests that galaxies with higher infrared luminosities have warmer dust temperatures, a trend we also see from our individual galaxies (see Figure 3.1). To better quantify this evolution, we fit each median...
Figure 3.6 Median SEDs from each infrared luminosity bin, all normalized so that $\nu L_\nu(1.6\mu m) = 6 \times 10^{10} L_\odot$. The factor that each SED was multiplied by (when compared to Figure 3.5) is shown on the right side of the plot. This plot emphasizes the differences in emission at both mid-infrared and far-infrared wavelengths between galaxies in different luminosity bins.

SED in $S_\nu$ using the C12 greybody fits and determine the average dust properties of these galaxies - infrared luminosity, peak wavelength, and dust mass. The results are listed in Table 4.1, and there is a clear trend in both dust mass and dust temperature toward hotter and more massive dust reservoirs with increasing infrared luminosity.

We also see the MIR ($\lambda_{\text{rest}} \sim 10$–20$\mu$m) portion of the SED increasing with $L_{\text{IR}}$, suggesting a stronger contribution from warm dust in the form of a MIR power-law. MIR power-law emission is generally thought to be dominated by emission from dust grains heated to extremely high temperatures ($\approx 1500$–2000$^\circ$K) in the dusty tori around AGN, and indeed we even see direct evidence of AGN in the SEDs of a non-negligible fraction of individual galaxies at the highest luminosities. In Figure 3.4, the two highest infrared
Table 3.1. Average Properties of Herschel-selected galaxies

<table>
<thead>
<tr>
<th>log($L_{\text{IR}}$) Range</th>
<th>⟨z⟩$^a$</th>
<th>⟨log($M_*$)⟩$^b$</th>
<th>log($L_{\text{IR}}$)$^c$</th>
<th>log($M_{\text{dust}}$)$^d$</th>
<th>$\lambda_{\text{peak}}$$^e$</th>
<th>$T_{\text{dust, grey}}$$^f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.00–10.99</td>
<td>0.30</td>
<td>10.4</td>
<td>10.8</td>
<td>7.6</td>
<td>140</td>
<td>27.8</td>
</tr>
<tr>
<td>11.00–11.49</td>
<td>0.56</td>
<td>10.5</td>
<td>11.4</td>
<td>8.0</td>
<td>124</td>
<td>32.8</td>
</tr>
<tr>
<td>11.50–11.99</td>
<td>0.93</td>
<td>10.6</td>
<td>11.9</td>
<td>8.4</td>
<td>112</td>
<td>37.5</td>
</tr>
<tr>
<td>12.00–12.49</td>
<td>1.46</td>
<td>10.8</td>
<td>12.4</td>
<td>8.4</td>
<td>86</td>
<td>53.2</td>
</tr>
<tr>
<td>12.50–13.49</td>
<td>2.19</td>
<td>10.9</td>
<td>12.8</td>
<td>8.8</td>
<td>85</td>
<td>54.1</td>
</tr>
</tbody>
</table>

Note. — (a) Median photo-z of all sources in $L_{\text{IR}}$ bin. (b) Median stellar mass of all sources in $L_{\text{IR}}$ bin from Ilbert et al. (2010, see Section 3.6.1). (c) $L_{\text{IR}}$ measured from C12 fits to median SED. (d) Dust mass measured from C12 fit to median SED. (e) Rest-frame SED peak wavelength of $S_{\nu}$ from C12 fit to median SEDs. (f) Dust temperature assuming a grey-body with $\beta = 1.5$ and $\tau = 1$ at 200 $\mu$m, derived from $\lambda_{\text{peak}}$ of median SEDs.

luminosity bins have some objects with data points at rest-frame UV wavelengths suggestive of a “big blue bump” commonly associated with AGN, and thought to be the thermal emission from an optically thick accretion disk surrounding a massive black hole (e.g. Shields 1978; Malkan & Sargent 1982). However, we note that these galaxies with putative AGN signatures still make up only a relatively small percentage of the sample and removing galaxies classified as AGN does not affect our median SEDs significantly.

Although we do not have the uniform wavelength coverage to make detailed comparisons across all luminosity bins, we also see possible PAH signatures at MIR wavelengths. In the two lowest luminosity bins, we see evidence of an emission feature at $\lambda_{\text{rest}} \approx 7$–$8\mu$m, presumably due to the strong PAH emission line at 7.71$\mu$m (Tielens et al. 1999). The SEDs for the two highest infrared luminosity bins also show hints of an absorption feature at $\lambda_{\text{rest}} \approx 10\mu$m that could possibly be explained as silicate absorption. We explore the variation of MIR features (specifically at $\lambda_{\text{rest}} \approx 8\mu$m) with $L_{\text{IR}}$ in more detail in Section 3.6.2.
An additional trend seen at shorter wavelengths is that at increasing infrared luminosities, the SEDs also have increased luminosity at optical and near-infrared (NIR: \( \lambda_{\text{rest}} \approx 2-5 \mu\text{m} \)) wavelengths. However, while the average infrared luminosities across our bins increase by a factor of \( \sim 100 \), the optical-NIR luminosities only increase by a factor of \( \sim 10 \). Near-infrared emission comes mostly from relatively older, cooler, and less massive stars that dominate the stellar mass of a galaxy, so this suggests that our more infrared luminous sources have larger stellar masses. To investigate this further, we normalize all of the median SEDs at 1.6\( \mu\text{m} \) to an arbitrary value of \( \nu L_\nu(1.6\mu\text{m}) = 10^9 L_\odot \) and plot the result in Figure 3.6. The relative difference between far-infrared luminosity and optical-NIR luminosity (or stellar mass) is clearly displayed, with the highest \( L_{\text{IR}} \) bins showing more than an order of magnitude difference between FIR luminosity and optical-NIR luminosity, while the lowest \( L_{\text{IR}} \) bin has almost equal FIR luminosity and optical-NIR luminosity. We explore the relationship between stellar mass (\( M_\ast \)) and \( L_{\text{IR}} \) in Section 3.6.1.

### 3.5.3 Trends with Redshift or Luminosity?

A major issue we must reconcile when studying our median SEDs is the degeneracy between redshift and infrared luminosity. As seen in Figure 3.3, redshift and infrared luminosity are correlated. This is because at low redshift, we do not cover enough volume to properly sample the high luminosity population, and at high redshift, the low luminosity galaxies fall below our detection limits. In addition, at low redshifts, the number density of high infrared luminosity galaxies drop dramatically, which makes detection of the highest luminosity galaxies difficult in the lowest redshift bins. Thus, it is possible that instead of witnessing evolution of SEDs with infrared luminosity, we are simply looking at galaxies at different redshifts that have evolving SEDs because of redshift evolution.

We tested if the trends with luminosity seen in Section 3.5.2 were actually due to redshift evolution by splitting each luminosity bin sample into redshift bins with width \( \Delta z = 0.5 \), and then constructing new median SEDs with the smaller subsamples. For every luminosity bin, we find that the new median SEDs in all redshift slices were consistent with each other,
and did not evolve significantly with redshift. This suggests that the main cause of the variation in SEDs is indeed the infrared luminosity of the objects.

3.6 Discussion

Our large sample of 4,218 Herschel-selected galaxies in the COSMOS field has permitted us to determine basic properties of luminous infrared galaxies at redshifts out to $z \sim 3.5$. Although this is not the first large sample of (U)LIRGs at high redshift, our analysis is the first to systematically investigate the median SED properties of (U)LIRGs as a function of $L_{\text{IR}}$ at these redshifts. One of the more surprising results from previous studies has been the suggestion that the majority of luminous infrared galaxies at high redshift form stars in a “normal main sequence mode”. Noeske et al. (2007) find a tight correlation between stellar mass ($M_*$) and star formation rate (SFR), and that this entire correlation shifts towards lower specific star formation rates ($sSFR \equiv SFR/M_*$) with time by a factor of $\sim 3$ from $z = 0.98$ to $z = 0.36$. Elbaz et al. (2011, hereafter E11) find that infrared luminous galaxies seem to fall on an “infrared main sequence” with a constant value of IR8, defined as the ratio of total infrared luminosity ($L_{\text{IR}}$) to luminosity at restframe 8$\mu$m ($L_8 \equiv \nu L_\nu(8\mu$m)).

At low redshifts, both of these “main sequence” relations appear to hold for galaxies with $L_{\text{IR}} < 10^{11.3}L_\odot$, but at higher infrared luminosities, galaxies systematically lie above both the $SFR/M_*$ “main-sequence” and the IR8 “infrared main sequence”. At higher redshifts, these “main sequences” appear to shift to higher SFRs (or $L_{\text{IR}}$), which means that LIRGs and ULIRGs begin to overlap with the main sequence, begging the question - are (U)LIRGs at high redshift simply scaled up versions of lower luminosity galaxies? This has many important implications for understanding star-formation at high redshift, and we wish to investigate these questions using our new large sample of objects.
3.6.1 Stellar Mass and Star Formation Rate

To investigate the relationship between $M_*$ and SFR for our complete sample of Herschel-selected galaxies, we use stellar masses from Ilbert et al. (2010), who use stellar population synthesis models from Bruzual & Charlot (2003) with an IMF from Chabrier (2003) and an exponentially declining star formation history, and we convert these masses to a Salpeter (1955) IMF by multiplying by a factor of 1.8 (as in Michałowski et al. 2012). We calculate total SFRs for each galaxy by combining their unobscured SFR from GALEX (Muzzin et al. 2013) with obscured SFR from $L_{\text{IR}}$ using the conversion

$$SFR(M_\odot \text{yr}^{-1}) = 4.5 \times 10^{-44} L_{\text{IR}}(\text{erg s}^{-1})$$

given in Kennicutt (1998), although due to our Herschel selection, the obscured star formation dominates the SFR in most of our galaxies. We plot SFR and $M_*$ of all our galaxies in Figure 3.7. For comparison, we also include “main sequence” lines for three redshift bins: $z \sim 0, 1, 2$ (Daddi et al. 2007; Elbaz et al. 2007).

At all redshifts, we see no evidence that the Herschel-detected galaxies in the COSMOS field concentrate on the nominal main-sequence trends plotted, but instead appear to have a much flatter distribution with stellar mass. We stress that Herschel observations of COSMOS generally sample only the most luminous regime of the SFR/$M_*$ plane, so we can not make any statements about galaxies at lower luminosities. Indeed, in a mass-selected sample, the Herschel-selected galaxies represent only a small percentage of the total number of galaxies (e.g. Rodighiero et al. 2011). However, our sensitivity in SFR is sufficient enough such that we should still see evidence of galaxies clustering or concentrating around the “main sequence” relation if such were the case. To demonstrate this, we model a population of 4000 galaxies at a redshift $z = 1$ with masses between $9.5 < \log(M_*) < 11.5$ that follow the SFR/$M_*$ main-sequence from Bouché et al. (2010), who provide a redshift-dependent functional form of the main-sequence. We then simulate our Herschel selection by removing all sources with SFR$< 50M_*/\text{yr}$, the approximate selection function at $z = 1$.
Figure 3.7 Stellar Mass vs. SFR of our entire Herschel sample, colored by redshift. Our redshift bins span $z < 0.5$ (purple), $0.5 < z < 1.5$ (blue), $1.5 < z < 2.5$ (yellow), and $2.5 < z < 3.0$ (red). Colored solid lines represent the “main-sequence” of galaxies at $z \sim 0$ (purple, Daddi et al. 2007), $z \sim 1$ (blue, Daddi et al. 2007), and $z \sim 2$ (yellow, Elbaz et al. 2007), and the horizontal dotted lines simply mark the star formation rates that correspond to the infrared luminosities of LIRGs, ULIRGs, and HyLIRGs.

(see Figure 3.1). Over 1000 such simulations, we find an average of 37% of the remaining simulated galaxies lie more than 0.3 dex off the main-sequence, with a maximum of 44%. In contrast, $\sim 60\%$ of our Herschel galaxies lie more than 0.3 dex above the redshift dependent main-sequence. Thus, we find almost twice as many galaxies above the SFR/$M_\star$ main-sequence as would be expected.

There are other previous studies of Herschel detected galaxies that also find that infrared luminous galaxies have a relatively flatter distribution across stellar mass than expected.
Rodighiero et al. (2011; Oteo et al. 2013b,a). However, Rodighiero et al. (2011) suggest that the presence of a large population of color-selected BzK galaxies that lie on the main-sequence dominate the number counts such that the overall population of star-forming galaxies still follows the general main-sequence trend. This may be the case at low masses, but at the high mass end where the main-sequence lies above the Herschel sensitivity limits, this cannot be the case unless there exists a large population of extremely UV bright, infrared dim objects with high star formation rates ($SFR > 100 \, M_\odot/yr$) that are missed by Herschel. A more likely explanation is that SFR indicators based on IR data, which directly measure the obscured star formation, differ greatly from SFR indicators that are based on measuring the unobscured star formation rate and applying a correction for dust. Indeed, for our sample of Herschel sources, we find that the optically derived total SFRs (corrected for dust) underpredict the far-infrared derived total SFR by an average factor of 2.7 (median)/9.6 (mean).

Because our sample is essentially a SFR selection, we cannot infer anything about the main-sequence below our selection limits. It may be that galaxies at low star formation rates follow the “main sequence”, but at star formation rates above a specific limit (e.g. $SFR > 100 \, M_\odot/yr$ at $z \sim 1$), galaxies deviate significantly from the main sequence, as seen in local galaxy samples (Larson et al. in prep). One possible physical explanation may be that the high star formation rates probed by Herschel observations require more extreme physical processes, such as galaxy mergers (Hung et al. 2013).

3.6.2 Mid-Infrared to Far-Infrared Diagnostics

Recent studies of Herschel-selected galaxies in GOODS-N and GOODS-S (E11, Nordon et al. 2012) have concluded that most infrared luminous galaxies at redshifts $z \sim 0–3$ have a constant ratio of total infrared luminosity ($L_{IR}$) to $\nu L_\nu$ at 8$\mu$m ($L_8$), defined as $IR8 \equiv L_{IR}/L_8$. E11 find that most infrared luminous galaxies at these redshifts follow a Gaussian distribution centered on $IR8 = 4$ ($\sigma = 1.6$), which they claim defines an “infrared main sequence for star-forming galaxies independent of redshift and luminosity”. Those few
galaxies which lie above the “infrared main sequence” were classified by E11 as a population of “compact starburst galaxies”, as opposed to more extended star-forming regions which were assumed to be representative of the larger population of galaxies on the “infrared main sequence”. E11 note that these new results were contrary to what is observed in samples of local infrared luminous galaxies, which show a constant IR8 value at infrared luminosities below $L_{\text{IR}} < 10^{11} L_{\odot}$, but have a systematic increase in IR8 at higher luminosities (see Figure 8 in E11). These results have contributed to the suggestion that the large majority of (U)LIRGs at high redshift form stars in a “normal main sequence” mode, as opposed to more local (U)LIRGs. We wish to test this important new result using our large sample of high-redshift infrared luminous galaxies.

As discussed in Section 3.5.2, we see hints that the MIR PAH features in the median SEDs of the Herschel-selected galaxies in the COSMOS field do in fact vary with infrared luminosity. However, our wavelength coverage is not sufficient to draw meaningful conclusions from the median SEDs alone. In order to compare our studies more directly, we calculate IR8 for each source in our sample. Since we do not have a direct measure of $\nu L_\nu$ at 8$\mu$m (rest frame) for all of our objects, we extrapolate from observed Spitzer MIPS 24$\mu$m or IRAC 8$\mu$m fluxes by assuming an SED shape. E11 used an M82 SED template for all of their extrapolations, but had additional coverage at 16$\mu$m from Spitzer IRS peak-up array imaging, in addition to Spitzer MIPS 24$\mu$m or IRAC 8$\mu$m observations, which means they required less extrapolations around $z \sim 1$. By measuring $L_8$ using extrapolations from both 16$\mu$m and 24$\mu$m for GOODS galaxies with observations at both wavelengths, we find that calculating $L_8$ from 24$\mu$m around $z \sim 1$ (as we do in COSMOS) generally matches the extrapolations from 16$\mu$m, with a scatter of a factor of $\sim 2$ and no systematic offset (private communication D. Elbaz).

Although a single SED template from M82 was used in E11, we were concerned about assuming a single SED template because rest-frame 8$\mu$m lies in a forest of PAH features, and the choice of model used for extrapolation could affect the results drastically. We demonstrate this in Figure 3.8, where we plot the extrapolation factors at different redshifts
when using SED templates from M82, Mrk231, Arp220 (Polletta et al. 2007), and star-formation SEDs from Brandl et al. (2006) and Pope et al. (2008). There can be a large variation in derived $L_8$ depending on which SED template is used. For the remainder of our analysis, we calculate $L_8$ for our galaxies by using the average $L_8$ calculated from the models of star-forming galaxies (Brandl et al. 2006; Pope et al. 2008, and M82), and using the standard deviation as an additional error in $L_8$. We also repeat all analyses using each single SED template in Figure 3.8 to see if the use of a particular template affects the results. We find that while the choice of template can affect broad changes (particularly around $z \sim 1.5$ due to fitting of the strong 10$\mu$m absorption feature), the overall trends we discuss do not differ significantly with the choice of model.

The results of our analysis are plotted in Figure 3.9, with the top plot displaying how $L_8$ varies with $L_{IR}$, and the bottom plot showing how IR8 varies with $L_{IR}$. In both plots, we have included a line displaying the “main sequence” from E11, and we see that our sources do not follow a single main sequence, as seen in E11, but instead seem to scatter to much higher IR8 values at infrared luminosities $L_{IR} \gtrsim 10^{11}L_{\odot}$, similar to what is seen in the local universe.

The trend we see in IR8 for Herschel-selected galaxies in COSMOS is actually very similar to the trend seen in local galaxies, where galaxies below $L_{IR} \sim 10^{11}L_{\odot}$ lie near the IR8 “infrared main sequence” and galaxies with higher infrared luminosities show a systematic increase in the value of IR8 vs. $L_{IR}$ (see Fig. 8 in E11). Could our results be due to a lack of depth in observations? When compared to the observations from the Great Observatories Origins Deep Survey fields (GOODS, E11) that the original “IR8 main-sequence” was based on, we see that we have shallower coverage at both 24 $\mu$m and in Herschel, but with much larger volume. It may be that sources with $L_{IR}$ below our far-infrared detection threshold will fall closer to the “IR8 main-sequence,” but at each redshift, these galaxies will necessarily fall to the left of the locus of points seen in the bottom panel of Figure 3.9, and will not be able to change the median location of those galaxies. It may also be possible that we are missing galaxies with similar $L_{IR}$ to our sample, but were not
Figure 3.8 The effects of SED template choice on correction factors when calculating $L_8 = \nu L_\nu(8\mu m)$. The different colors correspond to different templates that were used: Arp 220 (red), Mrk 231 (orange) and M82 (green) from the SWIRE template library (Polletta et al. 2007), mid-IR composite spectra from 13 SMGs from Pope et al. (2008, blue), and mid-IR composite spectra from starburst galaxies from Brandl et al. (2006, purple). The value plotted ($S_8/S_8(z = 2)$), gives the ratio of the correction factor applied at the desired redshift to the factor applied at a redshift of $z = 2$ (notice that every line crosses unity at $z = 2$). We compare to $z = 2$ because we have 24$\mu$m observations for each source, and at $z = 2$, the 24$\mu$m directly probes rest frame 8$\mu$m and so has limited correction factors anyway (slight corrections are needed to account for the different passbands in MIPS 24$\mu$m and IRAC 8$\mu$m). For redshifts below $z = 1$, we calculate corrections using the observed IRAC 8$\mu$m flux densities, while at all other redshifts we use the MIPS 24$\mu$m flux densities. This plot displays the dangers in assuming a single “star-forming” SED template to calculate $L_8$, as the template you choose can drastically affect the inferred luminosities.

detected because we require a 24 $\mu$m prior, and these galaxies have depressed $S_{24}$. However, these galaxies must necessarily have high IR8($= L_{IR}/L_8$) values, and will push our results even farther from the “IR8 main-sequence”.

It appears that galaxies at high redshift follow the same general trend as the local galaxies, with lower luminosity galaxies falling along the “IR8 main-sequence” and higher luminosity galaxies scattering to higher IR8, but the cutoff luminosity increases with redshift, due to the increasing gas density and star formation at earlier epochs in the
Universe. This interpretation might also explain the discrepancy between our results and those of E11. GOODS (∼ 260 arcmin²) is a much smaller field than COSMOS (∼ 2 deg²), but has PACS observations that are ∼ 3 times deeper than those of the COSMOS field. As a result of these discrepancies, GOODS observations are more sensitive to low luminosity galaxies, but do not have the volume coverage to find the rare, luminous sources, whereas Herschel-COSMOS observations cannot detect the lowest luminosity galaxies. Since the GOODS observations did not have enough volume to probe the high luminosity (high IR8) galaxies at any redshift, E11 find a “continuous” main sequence by combining the lower luminosity galaxies in each redshift slice. Although the Herschel-COSMOS observations do not have the sensitivity required to fully sample the lower luminosity galaxies that may lie on the IR8 “infrared main sequence,” there is sufficient volume coverage to better sample the high infrared luminosity population.

It seems that at the infrared luminosities probed by Herschel-COSMOS, the majority of luminous infrared sources at all redshifts do not follow either the $SFR/M_*$ “main sequence”, nor the IR8 “infrared main sequence”. In general, we see similar trends with $L_{\text{IR}}$ as observed for (U)LIRGs in the local universe, where galaxies with $L_{\text{IR}} \lesssim 10^{11} L_\odot$ lie on these “main sequences” while higher luminosity galaxies lie above the “main sequences”.

### 3.7 Conclusions

We have used new Herschel PACS & SPIRE observations of the large, contiguous 2 deg² COSMOS field in order to identify and study the multi-wavelength properties of 4,218 infrared luminous galaxies. Spitzer 24µm counterparts were used to match our Herschel sources to existing multi-wavelength photometry, allowing us to construct full rest-frame UV-to-FIR SEDs and determine accurate photometric redshifts. Our sources span a redshift range of $0.02 < z < 3.54$ and a total infrared luminosity range of $\log(L_{\text{IR}}/L_\odot) = 9.4-13.6$. We determine the basic properties of each galaxy (e.g. $L_{\text{IR}}$, $M_{\text{dust}}$, and $\lambda_{\text{peak}}$) by fitting their infrared SEDs to a coupled modified greybody plus a MIR power law. In order to
study the galaxy SEDs in more detail, we then compute median SEDs, binned by their total infrared luminosities.

From our detailed analysis of the COSMOS Herschel-selected galaxies, we find the following major results:

1. The SED peak wavelength systematically decreases from $\lambda_{\text{peak}} \sim 140\mu$m at $L_{\text{IR}} \sim 10^{10.8}L_{\odot}$ to $85\mu$m at $L_{\text{IR}} \sim 10^{12.8}L_{\odot}$. Over the same luminosity range, the dust mass systematically increases from $\log(M_{\text{dust}}/M_{\odot}) = 7.6$ to 8.8.

2. A comparison of the average luminosities at FIR wavelengths and at optical-NIR wavelengths shows that as $L_{\text{IR}}$ increases by a factor of 100 (from $L_{\text{IR}} = 10.8$–12.8), the stellar mass increases by only a factor of $\sim 3$ (from $\log(M*/M_{\odot}) = 10.4$–10.9).

3. At lower infrared luminosities ($\log L_{\text{IR}} < 11.5$), we see evidence of PAH features in the MIR ($\lambda_{\text{rest}} \approx 8\mu$m), which appear less significant at higher luminosities, where we see an apparent increasing contribution of hot dust ($T_{d} \sim 100$–300$^\circ$K) corresponding to the emergence of a power-law component at $\lambda_{\text{rest}} \approx 3$–30$\mu$m. At the highest luminosities ($L_{\text{IR}} > 10^{12}L_{\odot}$), we see a small, but increasing fraction of objects with prominent UV & optical excess, similar to the “big blue bump” seen in optically-selected QSOs.

4. We find no evidence that our Herschel-selected luminous infrared galaxies in COSMOS lie on the $SFR/M_*$ “main sequence” previously defined by studies of optically selected galaxies. About 60% of our luminous infrared galaxies lie more than 1$\sigma$ above the “main sequence” relationship.

5. We find no evidence that a constant value of IR8 ($\equiv L_{\text{IR}}/L_8$) applies to infrared luminous galaxies at high redshift. Instead, we find that at low infrared luminosities, galaxies have a constant value of IR8 ($\approx 4 \pm 1.6$), but at high infrared luminosities ($L_{\text{IR}} \gtrsim 10^{11.3}L_{\odot}$), galaxies systematically lie above the IR8 “infrared main sequence”, similar to what is seen for (U)LIRGs in the local universe.
This is the first in a series of papers that will explore in more detail the properties of infrared luminous galaxies across cosmic time. Future papers will study morphologies, spectral types, comparisons of UV/optical and far-IR derived SFRs, and comparisons of the high redshift population with complete samples of (U)LIRGs in the local universe ($z < 0.3$).

### 3.8 Acknowledgements

D. B. Sanders and C. M. Casey acknowledge the hospitality of the Aspen Center for Physics, which is supported by the National Science Foundation Grant No. PHY-1066293. C. M. Casey is generously supported by a Hubble Fellowship from Space Telescope Science Institute, grant HST-HF-51268.01-A.

COSMOS is based on observations with the NASA/ESA *Hubble Space Telescope*, obtained at the Space Telescope Science Institute, which is operated by AURA Inc, under NASA contract NAS 5-26555; also based on data collected at: the Subaru Telescope, which is operated by the National Astronomical Observatory of Japan; the XMM-Newton, an ESA science mission with instruments and contributions directly funded by ESA Member States and NASA; the European Southern Observatory, Chile; Kitt Peak National Observatory, Cerro Tololo Inter-American Observatory, and the National Optical Astronomy Observatory, which are operated by the Association of Universities for Research in Astronomy, Inc. (AURA) under cooperative agreement with the National Science Foundation; the National Radio Astronomy Observatory which is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.; and the Canada-France-Hawaii Telescope operated by the National Research Council of Canada, the Centre National de la Recherche Scientifique de France and the University of Hawaii.

PACS has been developed by a consortium of institutes led by MPE (Germany) and including UVIE (Austria); KU Leuven, CSL, IMEC (Belgium); CEA, LAM (France); MPIA (Germany); INAF-IFSI/OAA/OAP/OAT, LENS, SISSA (Italy); IAC (Spain). This
development has been supported by the funding agencies BMVIT (Austria), ESA-PRODEX (Belgium), CEA/CNES (France), DLR (Germany), ASI/INAF (Italy), and CICYT/MCYT (Spain).

SPIRE has been developed by a consortium of institutes led by Cardiff University (UK) and including Univ. Lethbridge (Canada); NAOC (China); CEA, LAM (France); IFSI, Univ. Padua (Italy); IAC (Spain); Stockholm Observatory (Sweden); Imperial College London, RAL, UCL-MSSL, UKATC, Univ. Sussex (UK); and Caltech, JPL, NHSC, Univ. Colorado (USA). This development has been supported by national funding agencies: CSA (Canada); NAOC (China); CEA, CNES, CNRS (France); ASI (Italy); MCINN (Spain); SNSB (Sweden); STFC (UK); and NASA (USA).
Figure 3.9 Top. A plot comparing $L_{\text{IR}}$ and $L_8$ for our Herschel COSMOS sources, with each symbol colored by redshift. The dashed line represents the relationship quoted in E11. We see that the majority of our detected sources fall off the E11 relationship, in general having much higher $L_{\text{IR}}$ than expected from the E11 relationship. Bottom. A plot detailing how $\text{IR8} \equiv L_{\text{IR}}/L_8$ changes with infrared luminosity, with colored dots representing the same sources as in the top plot. A running median of IR8 in bins of $L_{\text{IR}}$ is displayed with white circles. The black solid line represents the IR8 main-sequence defined by E11, with upper and lower limits drawn as black dotted lines. The maroon horizontal line represents the lower bound for galaxies deemed as “starburst” from their IR8. Typical uncertainties are plotted in the upper left hand corner.
References


Diolaiti, E. et al. 2000, A&AS, 147, 335 [3.3.1]


72


Chapter 4

A Turnover in the Galaxy Main Sequence of Star Formation at $M_\star \sim 10^{10} M_\odot$ for Redshifts $z < 1.3$

Published as Lee, Nicholas, Sanders, D. B., Casey, Caitlin M., Toft, Sune, Scoville, N. Z., Hung, Chao-Ling, Le Floc’h, Emeric, Ilbert, Olivier, Zahid, H. Jabran, Aussel, Herv, Capak, Peter, Kartaltepe, Jeyhan S., Kewley, Lisa J., Li, Yanxia, Schawinski, Kevin, Sheth, Kartik, Xiao, Quanbao 2015, 801, 80

4.1 Abstract

The relationship between galaxy star formation rates (SFR) and stellar masses ($M_\star$) is re-examined using a mass-selected sample of $\sim 62,000$ star-forming galaxies at $z \leq 1.3$ in the COSMOS 2-deg$^2$ field. Using new far-infrared photometry from Herschel-PACS and SPIRE and Spitzer-MIPS 24 $\mu$m, along with derived infrared luminosities from the NRK method based on galaxies’ locations in the restframe color-color diagram ($NUV - r$) vs. $(r - K)$, we are able to more accurately determine total SFRs for our complete sample. At all redshifts, the relationship between median $SFR$ and $M_\star$ follows a power-law at low stellar masses, and flattens to nearly constant SFR at high stellar masses. We describe a new parameterization that provides the best fit to the main sequence and characterizes the low mass power-law slope, turnover mass, and overall scaling. The turnover in the main sequence occurs at a characteristic mass of about $M_0 \sim 10^{10} M_\odot$ at all redshifts. The
low mass power-law slope ranges from 0.9-1.3 and the overall scaling rises in SFR as a function of $(1+z)^{4.12\pm0.10}$. A broken power-law fit below and above the turnover mass gives relationships of $SFR \propto M_*^{0.88\pm0.06}$ below the turnover mass and $SFR \propto M_*^{0.27\pm0.04}$ above the turnover mass. Galaxies more massive than $M_* \gtrsim 10^{10} M_\odot$ have on average, a much lower specific star formation rate (sSFR) than would be expected by simply extrapolating the traditional linear fit to the main sequence found for less massive galaxies.

### 4.2 Introduction

Over the last decade, a tight correlation between a galaxy’s star formation rate ($SFR$) and its stellar mass ($M_*$) has been discovered (Noeske et al. 2007; Daddi et al. 2007; Elbaz et al. 2007). Commonly referred to as the galaxy “main-sequence” (MS) of star formation, this relationship has important implications for the physical nature of star formation in galaxies. The MS is generally described as a single power law of the form $SFR \propto M_*^\beta$, with $\beta = 0.7–1.0$ and the normalization of the MS evolving to higher values at increasing redshift (Noeske et al. 2007).

A common interpretation of the existence and tightness of the main-sequence is that the majority of star-forming galaxies are powered by similar quasi-steady processes, with only a small fraction of galaxies undergoing more chaotic processes such as major merger events that might be expected to produce strong bursts of star formation (e.g. Elbaz et al. 2011; Rodighiero et al. 2011; Sargent et al. 2012). These starburst galaxies are generally thought to lie significantly above the MS and represent a minority of galaxies.

A key uncertainty in measuring galaxy SFRs is the effect of dust obscuration. The most direct method of determining dust obscuration is from observations in the far-infrared, where the absorbed starlight is thermally reradiated. In the absence of far-infrared data, various extrapolations from shorter wavelength have been used to study the main sequence, such as using emission lines combined with reddening corrections to infer the dust-corrected SFR (Brusa et al. 2010; Sobral et al. 2012; Zahid et al. 2012; Kashino et al. 2013) or measuring the
UV or optical emission from young massive stars and correcting for the radiation lost to dust obscuration (Lee et al. 2011; Rodighiero et al. 2011; Steinhardt et al. 2014). Observations in the mid-infrared (e.g. 24 μm) have been used to estimate far-infrared luminosities (e.g. Noeske et al. 2007; Daddi et al. 2007; Elbaz et al. 2007), although the accuracy of these estimates decreases at high redshifts and bright infrared luminosities (e.g. Papovich et al. 2007; Lee et al. 2010; Elbaz et al. 2011). Studies of radio emission take advantage of the well-known radio-FIR correlation (Helou et al. 1985; Condon 1992; Yun et al. 2001) to estimate the infrared luminosities, but many of these studies rely on stacking to overcome high sensitivity limits (Dunne et al. 2009; Pannella et al. 2009; Karim et al. 2011). The consensus from these studies is that the MS follows a single power law $SFR \propto M_\ast^\beta$, with the slope generally between $\beta = 0.7–1.0$ and the normalization varying based on the study’s redshift, SFR indicator, sample selection, and IMF (for a summary, see Speagle et al. 2014).

However, a few studies have found indications of a more complex main-sequence relationship. Some studies suggest that the MS slope varies with stellar mass so that a single power-law cannot explain the MS and a stellar mass-dependent slope is a better fit (Karim et al. 2011; Whitaker et al. 2012; Magnelli et al. 2014). Recent studies based on far-infrared selected samples from Herschel show that far-infrared selected galaxies lie mostly above the MS, with a much shallower slope in $\log(SFR)/\log(M_\ast)$ (Lee et al. 2013; Oteo et al. 2013a,b; Lemaux et al. 2013). However, this discrepancy is due to the flux limited selection of far-infrared samples that introduce a SFR-based selection bias, as compared to studies based on stellar mass-selected galaxy samples. This has been demonstrated by stacking analyses that explore the far-infrared emission as a function of stellar mass and find generally good agreement between dust-corrected UV-derived SFRs and Herschel-derived SFRs (e.g. Rodighiero et al. 2014).

Stacking is a commonly used technique to measure low-level emission from galaxies that would be undetected individually. Stacking analyses require a number of assumptions and can miss vital information about individual galaxies and their distributions. Unless the parent population is identical (a key assumption in stacking), interpretation of stacking
results can be difficult because the underlying distribution is unknown (although see Schreiber et al. 2014, for a possible method to determine the underlying distribution). In addition, these stacking analyses do not explain why the dust-corrected SFRs cannot accurately recover the SFRs seen in high luminosity galaxies, which have an elevated contribution to the integrated build up of stellar mass in the universe.

Direct Herschel FIR measurements remain a unique tool to properly estimate the ongoing star formation rate in the most active dusty galaxies. Analysis of the rest-frame UV emission in dusty galaxies suggests that applying the nominal attenuation laws (e.g. Meurer et al. 1999; Calzetti et al. 2000) will dramatically underestimate total star formation rate in galaxies exceeding \( \sim 50 \, M_{\odot}/\text{yr} \) (Smail et al. 2004; Casey et al. 2014; Rodighiero et al. 2014).

In the following paper, we attempt to address these issues by using a dust-corrected SFR indicator that is accurate for galaxies at all luminosities. By analyzing a large sample of individual galaxies, we do not lose information about the distribution of sources from stacking and can re-examine the shape of the star-forming MS in a stellar mass-selected sample. The data are described in Section 4.3 and SFRs computed by several different methods are measured and compared in Section 4.4. In Section 4.5 we analyze our mass-selected sample of galaxies in the \( SFR/M_* \) plane and find the best fits to the data. The implications of the main-sequence are discussed in Section 4.6 and we list our conclusions in Section 4.7. When calculating rest-frame quantities, we use a cosmology with \( \Omega_m = 0.28 \), \( \Lambda = 0.72 \), and \( H_0 = 70 \, \text{km} \, \text{s}^{-1} \, \text{Mpc}^{-1} \) (Hinshaw et al. 2013). A Chabrier (2003) Initial Mass Function (IMF) truncated at 0.1 and 100 \( M_{\odot} \) is used when deriving SFRs and stellar masses.

### 4.3 Data

Our analysis of the MS is made possible by the large area multi-wavelength coverage of the COSMOS field, a 2 \( \text{deg}^2 \) area of the sky with observations from the ultraviolet through
far-infrared and radio (Scoville et al. 2007). We construct a mass-complete sample of galaxies with $K_s < 24$ from the deep $K_s$-band catalog of Ilbert et al. (2013), based on data from the first UltraVISTA DR1 data release, covering \textasciitilde75\% of the COSMOS field (McCracken et al. 2012). 20 bands of optical and near-infrared photometry were extracted using matched apertures in dual-image mode from the various available COSMOS images and was combined with GALEX magnitudes from the multi-wavelength catalog of Capak et al. (2007). We use updated Spitzer IRAC photometry from the Spitzer Large Area Survey with Hyper-Suprime-CAM (SPLASH, Capak et al. in prep). We cross-match this catalog with the Spitzer MIPS 24 $\mu$m catalog of Le Floc’h et al. (2009) and the Herschel catalog of Lee et al. (2013) using a matching radius of 2\arcsec.

4.3.1 Source Selection

We interpolate the 90\% stellar mass completeness limits from Ilbert et al. (2013) to determine approximate mass completeness thresholds at all redshifts, and select only galaxies with stellar masses above their redshift dependent mass completeness limit. When studying star-forming galaxy populations, we separate “star-forming” and “quiescent” galaxies using a two-color selection technique: $NUV - r^+$ versus $r^+ - J$ (as described in Ilbert et al. 2013). Specifically, galaxies with absolute magnitude colors $M_{NUV} - M_r > 3(M_r - M_J) + 1$ and $M_{NUV} - M_r > 3.1$ are considered “quiescent” (\textasciitilde15\% of the sample) while the remaining galaxies are considered actively star-forming galaxies.

Star-forming galaxies that also contain luminous AGN are a concern because the luminosity from the AGN is extremely difficult to separate from emission from star-formation, and thus these sources may have erroneously high SFRs (although this concern is lessened for FIR sources because AGN generally heat dust to temperatures too hot to radiate in the far-infrared). On the other hand, many of the galaxies that host AGN also contain significant star-formation, and removing these sources introduces a bias to our study. We find that the overall results of our study are not significantly affected by either the inclusion or exclusion of these sources, so we do not remove galaxies that have been
detected in the X-ray (∼ 0.5% of sample) by XMM-Newton (Brusa et al. 2010) or Chandra (Civano et al. 2011), or that have IRAC power-law colors (Donley et al. 2008) that suggest AGN activity (∼ 25% of sample).

4.3.2 Infrared Data

The Herschel-selected sample of galaxies is described in detail in Lee et al. (2013, hereafter L13) and is briefly summarized here. L13 use Spitzer 24 µm and VLA 1.4 GHz priors to find 4,218 sources in COSMOS that were each detected in at least two of the five available Herschel PACS (100 µm or 160 µm) and SPIRE (250 µm, 350 µm, or 500 µm) bands. These sources span log(L_{IR}/L_⊙) = 9.4–13.6 and z = 0.02–3.54. Dust properties of each source (e.g. L_{IR}, T_{dust}, M_{dust}) were measured by fitting the full infrared photometry to a coupled modified blackbody plus mid-infrared power law using the prescription given in Casey (2012) and assuming an opacity model where τ = 1 at 200 µm.

There is a population of galaxies that are classified as “quiescent” from their NUV−r+ versus r+−J colors, but have been detected in the infrared by Herschel or Spitzer, suggesting that these galaxies are actually undergoing a significant amount of star-formation (∼ 7% of the “quiescent” population). These galaxies are more consistent with being very dusty objects that have extremely red colors due to obscuration, not lack of active star-formation, so we include these galaxies in our sample of star-forming galaxies (see Section 4.5.3).

4.3.3 Photometric Redshifts and Physical Parameters

Ilbert et al. (2013) measure accurate 30-band photometric redshifts of the full Ks-band COSMOS catalog. We find a median Δz/(1 + z) = 0.02 in our sample of star-forming galaxies, with a catastrophic failure (|Δz|/(1 + z) > 0.15) in 5.6% of sources. In addition, physical parameters such as stellar mass and star formation rate have been calculated by fitting the Spectral Energy Distributions (SEDs) to synthetic spectra generated using the Stellar Population Synthesis (SPS) models of Bruzual & Charlot (2003). We also recalculate the physical parameters using different templates and extraction parameters, and find that
our final results are not affected by the specific choice of template. Thus, we use the same set of parameters used to create the catalog in Ilbert et al. (2013), but with updated near-IR photometry from SPLASH.

4.4 Analysis

4.4.1 Star Formation Rate Calculations

There are many methods for estimating a galaxy’s SFR based on observations at various wavelengths (for a review, see Kennicutt 1998; Murphy et al. 2011). Here we compare a few commonly used SFR indicators using a subset of COSMOS galaxies to determine how much the different SFR methods disagree. In all cases, we measure the total SFR as

\[ SFR_{\text{Total}} = SFR_{\text{IR}} + SFR_{\text{UV}}. \]

Infrared derived SFR

As discussed in Section 4.3.2, the infrared properties of the Herschel-selected galaxies have been measured by fitting the infrared SEDs to a coupled modified blackbody plus mid-infrared power law model (Casey 2012). It has been shown that measuring the \( L_{\text{IR}} \) from fitting the far-infrared data to libraries of SED (e.g. Chary & Elbaz 2001; Dale & Helou 2002) gives roughly the same results as the modified blackbody plus power-law model (Casey 2012; U et al. 2012; Lee et al. 2013). The infrared observations give us an estimate of the obscured SFR, and we combine this with UV observations of the unobscured SFR to derive the total SFR as in Arnouts et al. (2013):

\[ SFR_{\text{Total}} = (8.6 \times 10^{-11}) \times (L_{\text{IR}} + 2.3 \times \nu L_{\nu}(2300\text{Å})) \]  

(4.1)

where \( L_{\text{IR}} \equiv L(8\text{–}1000\mu m) \) and all luminosities are measured in units of \( L_\odot \). For sources with \( SFR \gtrsim 50M_\odot/yr \), the infrared contribution dominates the total SFR, contributing as much as \( \sim 90\% \) of the total SFR.
While we have excellent *Herschel* coverage of the full 2-deg$^2$ COSMOS field that yields 4,218 sources, the detection limits of *Herschel* introduce a selection bias against all but the most luminous infrared sources. A common method of determining the $L_{\text{IR}}$ of less luminous galaxies is to use deep *Spitzer* 24 μm data to estimate the far-infrared luminosity (e.g. Kennicutt et al. 2009; Ricke et al. 2009; Rujopakarn et al. 2013). COSMOS has extremely deep coverage at 24 μm and Le Floc’h et al. (2009) provide SFR estimates for 36,635 galaxies, which we use to extend our sample of infrared detected galaxies to more moderate luminosities.

**Optical & UV based SFR Indicators**

For galaxies without direct measurements from far- or mid-infrared wavelengths of the obscured SFR, the amount of radiation obscured by dust must be estimated indirectly. A common method for estimating total SFR is to fit libraries of model SEDs (that include prescriptions for dust obscuration) to optical & UV photometry. Ilbert et al. (2013) use the full optical COSMOS photometry and fit to a library of synthetic spectra from Bruzual & Charlot (2003), and estimate the total SFR for each of the galaxies in our sample from the best fit SEDs.

Another method of estimating dust-corrected SFRs is by using rest-frame UV observations to measure the unobscured SFR and inferring the appropriate dust correction factor from observed colors. Two examples of this are the BzK method from Daddi et al. (2004) and the NRK method from Arnouts et al. (2013). BzK SFRs are determined by using the observed-frame $B$-band photometry to measure the rest-frame UV luminosity, and then estimating the extinction as $E(B-V) = 0.25(B - z + 0.1)_{\text{AB}}$ (Daddi et al. 2007). BzK SFRs are only valid for redshifts $1.4 < z < 2.5$, as these are the only redshifts where the desired portions of the SED are redshifted to the correct wavelengths, and we limit our selection to the good-sBzK with errors $\delta \log [\text{SFR(UV)}] < 0.3$ dex (Rodighiero et al. 2014).

NRK SFRs are calculated by using their location in the rest-frame color-color diagram ($NUV - r$) vs. $(r - K)$ to estimate extinction. Arnouts et al. (2013) find that at $z \leq 1.3$,
the infrared excess \( \text{IRX} \equiv \frac{L_{\text{IR}}}{L_{\text{NUV}}} \) in star-forming galaxies can be parameterized as a function of redshift and the vector \( \text{NRK} = 0.31 \times (\text{NUV} - r) + 0.95 \times (r - K) \). This allows us to estimate the \( L_{\text{IR}} \) and calculate total SFR using Equation 4.1. When measuring NRK SFRs, we use the small “sSFR correction” as described in Arnouts et al. (2013).

### 4.4.2 Comparison of SFR indicators

We compare commonly used SFR indicators using a common subset of COSMOS galaxies to determine how much agreement there is between the different measures of SFR. We have a large set of Herschel detected galaxies from Lee et al. (2013) where, for the first time, we have direct measurements of both the obscured and unobscured SFR (from UV observations) at a wide range of redshifts. We compare the other SFR indicators discussed previously (24 µm, SED fits, BzK, and NRK) to this sample of 4,218 Herschel detected galaxies.

Figure 4.1 displays the comparison of \( SFR_{\text{Total}} \) from the four different indicators discussed above to \( SFR_{\text{Total}} \) as measured by Herschel. Density contours show the location and concentration of the majority of the sources, with outliers shown in gray circles. Median values in 20 equally populated bins of \( SFR_{\text{Total,Herschel}} \) are over-plotted to show average trends. To determine the strength of the correlation between each SFR indicator and \( SFR_{\text{Total,Herschel}} \), we measure the Pearson correlation coefficient (\( \rho \)) and provide these values at the top of each sub-panel. The Pearson correlation coefficient can vary between +1 and -1, with +1 indicating total positive correlation, 0 indicating no correlation, and -1 indicating total negative correlation. We also measure the median difference between each SFR indicator and Herschel SFR (\( < \Delta \log(SFR) > \)) and list these values at the top of each sub-panel.

The 24 µm-determined SFR correlates with the Herschel SFR very well (\( \rho_{24} = 0.88 \), \( < \Delta \log(SFR_{24}) > = 0.12 \)), except at the highest IR luminosities. This trend has been previously explored in many studies which find that at moderate redshifts and IR luminosities, 24 µm observations are a good proxy for \( L_{\text{IR}} \), but at high redshifts and
Figure 4.1 Comparison of total SFR determined from combining direct measurements of FIR (Herschel, Lee et al. 2013) and UV (GALEX, Zamojski et al. 2007) with various SFR indicators using observations at shorter wavelengths. The different SFR indicators are: [top left] Spitzer 24 µm (Le Floc’h et al. 2009) + GALEX; [top right] multi-wavelength SED fits (Ilbert et al. 2013); [bottom left] NRK (0 < z < 1.3, Arnouts et al. 2013); and [bottom right] BzK (1.4 < z < 2.5, Daddi et al. 2007). In each panel, black contours give the density and concentration of sources, with extreme outliers plotted as gray circles. We bin the data in 20 equally populated bins (except BzK, which has 8 bins) and find the median SFR\textsubscript{indicator} in each bin. Errors on the median points are measured using a bootstrapping technique and are plotted when larger than the size of the symbol. At the top of each panel is the Pearson correlation coefficient (with a value of +1 indicating strong positive correlation and 0 indicating no correlation) and the typical difference between each particular SFR indicator and the Herschel-derived SFR.
infrared luminosities, the 24 µm estimates tend to overpredict the true $L_{\text{IR}}$, possibly due to redshifting of the observed 24 µm-band to wavelengths contaminated by PAH features (e.g. Papovich et al. 2007; Lee et al. 2010; Elbaz et al. 2011). As we are using the 24 µm SFRs to fill in the low and moderate luminosity galaxies that are not detected with Herschel, this discrepancy is not a major issue for our work.

The NRK SFRs also show strong correlation with the Herschel-derived SFRs ($\rho_{\text{NRK}} = 0.79$, $< \Delta \log(SFR_{\text{NRK}}) > = 0.17$). This is not completely unexpected since the NRK method was developed using 24 µm-derived SFRs as a baseline, but the NRK measured SFRs match very well with those derived from Herschel. Like with $SFR_{24}$, the correlation shows signs of breaking down at the highest SFRs, but as long as the NRK is used mainly for low SFR galaxies, it provides a reliable estimate of the SFR.

By contrast, the agreement between $SFR_{\text{SED}}$ and $SFR_{\text{Total}}$ is quite poor, showing much weaker correlation between the two indicators ($\rho_{\text{SED}} = 0.56$). The tightness of the correlation is also much broader ($< \Delta \log(SFR_{\text{SED}}) > = 0.43$), even at low SFRs where the median points lie closer to the unity line. Again, at high SFRs the median points show a clear deviation from unity. Wuyts et al. (2011) are able to find a better match between $SFR_{\text{SED}}$ and $SFR_{24}$ if they tune key parameters of the SED fit, such as $\tau_{\text{min}}$, the $e$-folding time of the exponentially declining star formation history. The exact tuning needed varies based on several other assumptions in the SED fitting procedure, such as different stellar population synthesis codes, and even when the tuning is done, the computed $SFR_{\text{SED}}$ still systematically underestimates the true SFR for a significant fraction of sources.

Finally, the comparison between $SFR_{\text{BzK}}$ and $SFR_{\text{Total}}$ shows essentially no correlation ($\rho_{BzK} = -0.11$). It should be noted that the redshift range of the BzK indicator (1.4 < $z$ < 2.5) limits us to a small sample size containing only the brightest galaxies. As seen in Figure 4.2, this selection limits our comparison to galaxies at SFRs where all indicators begin to deviate significantly from $SFR_{\text{Total}}$. Stacking analyses suggest a stronger correlation between average $SFR_{\text{BzK}}$ and average $SFR_{\text{Herschel}}$ at fainter luminosities (Rodighiero et al. 2014), but the tightness of the distribution is not well determined. The
BzK galaxies that are *Herschel* detected show no correlation between the SFR derived from the BzK method and from *Herschel* measurements.

Figure 4.2 Median difference in SFR estimated from infrared vs. optical/UV indicators, as a function of Total SFR. Sources that were detected by both SFR indicators were split in 15 equally populated $SFR_{\text{Total}}$ bins, and the median value is plotted, with error bars representing bootstrapped errors. We see that all indicators begin to deviate significantly at $\log(SFR) \gtrsim 1.5$. (Top) Comparison of Spitzer 24 µm + GALEX (blue), multi-wavelength SED fits (green), NRK (orange, $0 < z < 1.3$), and BzK (red, $1.4 < z < 2.5$) to total SFR as derived from *Herschel*. (Bottom) Comparison of multi-wavelength SED fits (green), NRK (orange, $0 < z < 1.3$), and BzK (red, $1.4 < z < 2.5$) to total SFR as derived from Spitzer 24 µm.
Selection Effects of SFR Indicators

The comparisons of the various SFR indicators shown in Figure 4.1 span different dynamic ranges in SFR, mostly due to the redshift limitations of the NRK and BzK indicators. In Figure 4.2, we plot the typical difference between SFR indicators and $SFR_{\text{Total}}$ as a function of $SFR_{\text{Total}}$. We see that all of the SFR indicators provide poor estimates of the infrared measured $SFR_{\text{Total}}$ above $\log(SFR) \gtrsim 1.5$ ($\sim 30M_\odot$/yr). These common SFR indicators fail to accurately estimate the true SFR of luminous infrared galaxies. This highlights the need for direct infrared observations to accurately measure the SFR of highly star forming galaxies.

Throughout this analysis we have assumed the Herschel-determined SFR is the most accurate because it directly probes far-infrared wavelengths, where the bulk of the re-radiated radiation from dust is emitted. However, it is possible that the high detection threshold of Herschel limits us to a biased sample that does not accurately reflect the emission properties of lower luminosity galaxies. To test this possibility, we re-run our analyses using the much deeper sample of Spitzer 24 $\mu$m-detected galaxies (which showed excellent agreement with Herschel SFRs) as the comparison sample. We find very similar results as the Herschel comparison, with NRK providing both the strongest correlation and the tightest distribution.

A Ladder of SFR Indicators

While all three non-infrared based SFR indicators fail to accurately estimate the SFR in high luminosity galaxies, the NRK method provides the most accurate and consistent estimates across the full dynamical range of Herschel SFRs. At high SFRs ($SFR \gtrsim 30M_\odot$/yr), 70% of our sample is directly detected in the infrared by either Herschel or Spitzer. Thus, we can study the full population of star forming galaxies by constructing a “ladder” of SFR indicators (as in Wuyts et al. 2011) based on the Herschel, Spitzer 24 $\mu$m, and NRK SFR indicators. All sources have $SFR_{\text{Total}}$ calculated using Equation 1, with different methods of determining $L_{IR}$. For sources detected by Herschel, we measure $L_{IR}$ from fitting the
far-infrared photometry to the Casey (2012) greybody plus power-law models. We use the $L_{\text{IR}}$ estimated from 24 $\mu$m (Le Floc’h et al. 2009) for sources that are not detected by Herschel but are detected at Spitzer 24 $\mu$m. And for the remaining sources, we estimate the $L_{\text{IR}}$ using the NRK-derived IRX (as discussed in Section 4.4.1). Although we include NRK-derived IRX for all galaxies above our mass-completeness limits, the method has only been well-calibrated for $M_* > 10^{9.3} M_\odot$. Infrared stacking suggests that any systematic offsets should be small, but when calculating main sequence relationships we only include galaxies with $M_* > 10^{9.3} M_\odot$.

The relative fraction of sources with SFRs measured from each indicator is plotted in Figure 4.3 as a function of both stellar mass and redshift. Below $M_* \lesssim 10^{9.5} M_\odot$, SFRs are almost all determined from NRK, but at higher stellar masses, the fraction of sources with direct infrared measurements increases until about 25% (60%) of sources at $M \gtrsim 10^{10.5} M_\odot$ have SFRs determined from Herschel (Spitzer 24 $\mu$m). Because of the redshift limitations of the NRK method (see Arnouts et al. 2013) and the larger errors associated with the SFR$_{\text{SED}}$ and SFR$_{\text{BzK}}$ indicators, we restrict the rest of our analysis to redshifts $0 < z < 1.3$, where we can more accurately measure the SFR of our full sample.

4.5 Shape of the Main Sequence of Star Formation

With reliable and consistent SFR estimates for a large, mass-complete sample of galaxies in COSMOS, we examine the star-forming main sequence for a large, unbiased sample of 62,521 galaxies. Figure 4.4 displays the stellar mass and SFR of our full sample, split into four redshift bins spanning $0.2 \leq z \leq 1.3$. Black contours display the density of sources at each location in SFR and $M_*$ parameter space, and colored bars represent the median SFR in stellar mass bins of width $\Delta \log(M_*) = 0.3$, with vertical error bars displaying the standard deviation of the SFRs in that bin. These same bins are used to create the fractional histograms plotted on the side of each redshift bin, which display the distribution of SFRs within each mass bin with the corresponding color. The derived main sequence
Figure 4.3 Relative fraction of sources with SFRs determined from NRK (dotted line), Spitzer 24 μm (dashed line), and Herschel (solid line). Different colored lines represent percentages in different redshift bins, with bluer colors representing low redshifts and redder colors representing high redshifts.

relationships from star-forming galaxies in Karim et al. (2011) and Whitaker et al. (2014) are also plotted for comparison.

Figure 4.4 shows that the galaxies in our sample do not follow a simple linear main sequence relationship between $\log(SFR)$ and $\log(M_*)$ (or a single power-law relationship between $SFR$ and $M_*$). Instead, the median SFR relationship appears to flatten at masses above $M_* \sim 10^{10} M_\odot$. This can be seen in the histograms, which show that the peak of
Figure 4.4 Contour density plot of star-forming galaxies in the COSMOS field. We remove all galaxies classified as “quiescent” (unless they were detected in the infrared) and combine all star-forming galaxies, regardless of the specific SFR indicator used. To display the density of sources in the SFR/M* plane, each redshift slice was made into a grid of 51 × 51 bins, and the number of sources in each bin was calculated. Black contours show the density of galaxies, with contour levels set at 1/2 of the standard deviation of the number of sources in each bin. Colored vertical bars represent the median SFR in mass bins of width 0.3 dex and display the overall trend of the SFR/M* relationship. Histograms of matching color display the distribution of SFR in each mass bin along the sides of each plot. Main-sequence relationships from Karim et al. (2011, green dots) and Whitaker et al. (2014, blue line) are plotted for comparison.

Each SFR distribution increases with increasing M*, at low masses, but at high masses, the histogram peaks all lie at approximately the same SFR. The standard deviation of the SFR in each stellar mass bin remains mostly constant at all masses and at all redshifts, with
\( \sigma \sim 0.36 \) dex in all bins. The shape of this relationship appears roughly constant with redshift, with the entire relationship increasing to higher SFRs at higher redshifts.

### 4.5.1 Parameterizing the Star-Forming Main Sequence

From Figure 4.4, it is clear that a single power-law does not accurately describe the relationship between stellar mass and star formation rate. We split our sample of star-forming galaxies into 6 equally populated redshift bins, each of which are then split into 30 equally populated stellar mass bins (with \( \sim 350 \) sources in each bin), and calculate the median SFR in each bin. We limit our sample to stellar masses above a conservative mass limit (see Table 4.1) to ensure that we are not affected by systematics. The specific number of redshift bins does not affect the following results, although we must balance between having redshift bins that are too wide and combine galaxy samples at different epochs with having redshift bins that are too narrow and are affected by small number statistics. The same is true for the number of stellar mass bins, although having at least 30 bins is preferable for accurately determining the goodness of fit to the models. The median SFRs for every bin are plotted in Figure 4.5, colored by redshift, with bootstrapped errors on the median represented by vertical bars.

Using the MPFIT package implemented in IDL (Markwardt 2009), we fit the median \( \log(M_*) \) and \( \log(SFR) \) in each redshift bin with many models including linear, 2nd order polynomial, and broken linear, and find the best fit is provided by the following model:

\[
S = S_0 - \log \left[ 1 + \left( \frac{10^\mathcal{M}}{10^{M_0}} \right)^{-\gamma} \right]
\]

(4.2)

where \( S = \log(SFR) \) and \( \mathcal{M} = \log(M_*/M_\odot) \). We choose this model because (1) at all redshifts, it provides the best reduced \( \chi^2 \) fit to the data, and (2) unlike polynomial fits, the parameters of the model allow us to quantify the interesting characteristics of the relation between stellar mass and SFR: \( \gamma \), the power-law slope at low stellar masses, \( M_0 \), the turnover mass (in \( \log(M_*/M_\odot) \)), and \( S_0 \), the maximum value of \( S \) (or the maximum value
Table 4.1. Average Properties of Herschel-selected galaxies

<table>
<thead>
<tr>
<th>Redshift Range</th>
<th>(&lt;z\rangle)</th>
<th>(\log(M_{\text{limit}}/\odot))</th>
<th>(\mathcal{S}_0)</th>
<th>(\gamma)</th>
<th>(M_0)</th>
<th>Reduced (\chi^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25–0.46</td>
<td>0.36</td>
<td>8.50</td>
<td>0.80 ± 0.019</td>
<td>10.03 ± 0.042</td>
<td>0.92 ± 0.017</td>
<td>1.74</td>
</tr>
<tr>
<td>0.46–0.63</td>
<td>0.55</td>
<td>9.00</td>
<td>0.99 ± 0.015</td>
<td>9.82 ± 0.031</td>
<td>1.13 ± 0.033</td>
<td>1.52</td>
</tr>
<tr>
<td>0.63–0.78</td>
<td>0.70</td>
<td>9.00</td>
<td>1.23 ± 0.016</td>
<td>9.93 ± 0.031</td>
<td>1.11 ± 0.025</td>
<td>1.48</td>
</tr>
<tr>
<td>0.78–0.93</td>
<td>0.85</td>
<td>9.30</td>
<td>1.35 ± 0.014</td>
<td>9.96 ± 0.025</td>
<td>1.28 ± 0.034</td>
<td>1.84</td>
</tr>
<tr>
<td>0.93–1.11</td>
<td>0.99</td>
<td>9.30</td>
<td>1.53 ± 0.017</td>
<td>10.10 ± 0.029</td>
<td>1.26 ± 0.032</td>
<td>0.62</td>
</tr>
<tr>
<td>1.11–1.30</td>
<td>1.19</td>
<td>9.30</td>
<td>1.72 ± 0.024</td>
<td>10.31 ± 0.043</td>
<td>1.07 ± 0.028</td>
<td>1.24</td>
</tr>
</tbody>
</table>

Note. — Parameters of the best fit model to the star-forming main sequence. The full sample of 62,521 star-forming galaxies is split into six equally populated bins, with each bin containing \(\sim 17,745\) galaxies. Within each redshift bin, the galaxies are split into 30 equally populated bins of stellar mass. The median SFR in each mass bin is calculated and then fit to \(S = S_0 - \log\left(1 + \left(\frac{M^*}{M_{\odot}}\right)^{-\gamma}\right)\), where \(S = \log(SFR)\) and \(M = \log(M_*).\) Table columns are as follows: (1) Redshift range of bin; (2) Median Redshift; (3) Stellar Mass Limit of redshift bin; (4) \(S_0,\) the maximum value of \(S;\) (5) Turnover Mass; (6) Low-mass power-law slope; (7) Reduced \(\chi^2\) of fit.

4.5.2 Evolution of Model Parameters

In the top panels of Figure 4.6, we plot the evolution of \(S_0, \ M_0,\) and \(\gamma\) as functions of \(\log(1+z).\) The bottom panels of Figure 4.6 examine the covariance between these parameters by displaying the 95% confidence error ellipses.

We see clear and strong evolution of \(S_0\) with redshift, and the best fit line suggests an evolution of \(S_0 \propto (4.12 \pm 0.10) \times \log(1+z),\) or equivalently, \(SFR_0 \propto (1+z)^{4.12\pm0.10}.\) The covariance between \(S_0\) and \(M_0\) (Figure 4.6D) and between \(S_0\) and \(\gamma\) (Figure 4.6E) is relatively minor, so we infer that the evolution in \(S_0\) is true evolution and not due to variation in the other parameters.

Both \(M_0\) and \(\gamma\) show some evidence for weak evolution to more massive \(M_0\) and steeper \(\gamma\) with redshift, although much of the perceived evolution may be due to the covariance seen in Figure 4.6F. The best (linear) fit to the evolution in the turnover mass is given by
Figure 4.5 Median SFR in 6 equally populated redshift bins that have been split into 30 equally populated stellar mass bins. Errors on the median are calculated from bootstrapping. Solid lines represent the best-fit curve to the model $S = S_0 - \log \left[ 1 + \left( \frac{10^{M}}{10^{M_0}} \right)^{-\gamma} \right]$. Vertical dashed line represents the stellar mass limit below which NRK has not been well-calibrated.

$M_0 \propto (1.41 \pm 0.20) \times log(1+z)$. We test the possible redshift evolution of turnover mass by calculating where the data deviates by 0.2 dex from a single power-law fit to the low mass data and find similar evolution, suggesting that the turnover mass does indeed change with cosmic time. The low-mass power-law slope, $\gamma$, has a best-fit line that suggests evolution of $\gamma \propto (1.17 \pm 0.13) \times log(1+z)$. Redshift evolution in $\gamma$ to steeper slopes at earlier cosmic
times would suggest that the SFR in the lowest stellar mass galaxies does not increase as much as in more massive systems.

Figure 4.6 **Top:** Redshift evolution of the best-fit parameter values for (A) maximum of \(\log(SFR)\), \(S_0\); (B) turnover mass, \(M_0\); and (C) power-law slope, \(\gamma\). Different color dots represent parameter values in different redshift bins with 1-\(\sigma\) error bars, and the dotted line is the best-fit linear fit to the data. **Bottom:** 95% confidence error ellipses displaying the covariance between (D) \(S_0\) and \(M_0\); (E) \(S_0\) and \(\gamma\); and (F) \(\gamma\) and \(M_0\), with different colors once again representing different redshift bins. We see moderate covariance in \(\gamma\) and \(M_0\), but little covariance between the other pairs.

### 4.5.3 Separating Quiescent Galaxies

We have described the main sequence relationship between \(SFR\) and \(M_*\) for *star-forming* galaxies. However, possible misclassification of galaxies as either “star-forming” or “quiescent” could drastically affect the trends we observe.

As described in Section 4.5, we remove galaxies that are considered quiescent from our sample using the selection \(M_{NUV} - M_r > 3(M_r - M_J) + 1\) and \(M_{NUV} - M_r > 3.1\) (Ilbert et al. 2013). This selection is shown in Figure 4.7, with the full mass-selected sample of
COSMOS galaxies at $0.2 < z < 1.3$ generally separated into two distinct “star-forming” and “quiescent” regions. Improper classification of the “in-between” galaxies that are not obviously star-forming or quiescent could lead to changes in the main sequence shape. To test this possibility, we shift the entire separating line (both horizontal and diagonal segments) between quiescent and star-forming galaxies by $\pm 0.4$ mag in $M_{\text{NUV}} - M_r$, and in either case there is no appreciable change to the main-sequence.

Figure 4.7 $\text{NUV} - r^+$ vs. $r^+ - J$ plot of a mass-selected sample of galaxies in COSMOS at $0.2 < z < 1.3$. Black contours represent the full sample of galaxies, while orange circles highlight galaxies that are IR-detected, either with Herschel or Spitzer 24 $\mu$m. The red line, from I13, divides the sample into “star-forming” and “quiescent” galaxies. The majority of IR-detected galaxies are properly classified as “star-forming”, but there is a significant population ($\sim 7\%$) that are misclassified as “quiescent”.

Galaxies detected in the infrared by Herschel or Spitzer 24 $\mu$m are highlighted in Figure 4.7, and while the majority fall on the star-forming sequence, we see a number of objects that lie in the quiescent region. This population of infrared-detected quiescent (IR-Q) galaxies is relatively small, with only $\sim 7\%$ of the galaxies classified as quiescent having
detectable infrared emission, but these misclassified galaxies are predominantly found at high stellar mass. The fraction of quiescent galaxies detected in the infrared increases rapidly from $\leq 1\%$ at $M_\ast \sim 10^{9.5} M_\odot$ to $15-20\%$ at $M_\ast \geq 10^{11} M_\odot$, and this trend holds at all redshifts. These massive galaxies could heavily influence the shape of the main-sequence we observe, so it is vital to understand what is driving their infrared emission.

There could be several reasons why galaxies with quiescent colors have significant emission in the infrared, including (i) improper classification of star-forming galaxies possibly due to extreme dust obscuration, (ii) elevated infrared luminosity from an AGN, (iii) inaccurate absolute magnitudes due to catastrophic failures in photo-z’s or low signal-to-noise photometry, or (iv) “post-starburst” infrared glow due to dust heating from young stars (that is not related to the instantaneous star formation).

AGN typically heat dust to very hot temperatures, so we expect any AGN contribution to infrared radiation to be predominantly in near- and mid-IR wavelengths, while far-infrared emission is likely due to star formation alone. Only about $10\%$ of the IR-Q galaxies have been detected by Herschel, and the rest are 24 $\mu$m-only detections, where AGN may heavily influence the emission. However, only $\sim 1-5\%$ of the IR-Q galaxies are detected in the X-ray by Chandra, and only $\sim 2-8\%$ of the IR-Q galaxies have IRAC power-law colors indicative of AGN, with significant overlap in those two populations, and the percentages are even lower when looking only at the 24 $\mu$m-only sources. This suggests that radiation from an AGN is not fueling the infrared emission. The average SFR of the IR-Q galaxies with AGN is $0.2-0.5$ dex higher than the average SFR of all the IR-Q galaxies, so the presence of AGN in these galaxies is likely just a reflection of the well-studied trend that AGN fraction increases with SFR or $L_{\text{IR}}$ (e.g. Kartaltepe et al. 2010).

The rather high SFRs of the IR-Q galaxies suggest that they are indeed driven by star-formation, and have been misclassified as quiescent. Man et al. (in prep) stack the infrared emission from quiescent galaxies and find upper limits of $SFR_{\text{IR}} < 0.1–1 M_\odot$/yr. The SFRs of the IR-Q galaxies in our sample tend to lie below the main-sequence, but are all at least $\times 2–3$ higher than the upper limit from Man et al., which suggests that they are indeed
still actively star-forming. In addition, the infrared emission from IR-Qs is brighter than expected from a “post-starburst” glow (Hayward et al. 2014). It is unlikely that catastrophic photo-z errors or low signal-to-noise photometry are causing these misidentifications, as the sources have excellent photometry and well-constrained photometric redshifts (only 0.1% of the IR-Q galaxies have $\sigma_{\Delta z/(1+z)}>0.15$). Thus, the likely explanation for these sources is that they are actively star-forming galaxies that have been misclassified as “quiescent”, and we include them in our analysis of the main-sequence. We note, however, that the shape of the main-sequence does not change significantly based on the inclusion or exclusion of these sources.

4.6 Discussion

We see that the slope of the main sequence relationship between $SFR$ and $M_*$ changes with stellar mass. While most previous studies found a constant main sequence slope (for a summary see Speagle et al. 2014), some recent studies found a curved relationship might provide a better fit to the data (Karim et al. 2011; Whitaker et al. 2012). However, the mass completeness limit in both studies coincided with the turnover mass, leaving doubt as to whether the turnover was a real trend or an artifact of completeness. With our new COSMOS observations, we are able to study star-forming galaxies considerably less massive than the turnover mass, and we find that a single power-law does not provide the best description of the star-forming main-sequence.

4.6.1 The Turnover in the Star-Forming Main Sequence

The relationship between SFR and $M_*$ varies with stellar mass, with two distinct regions below and above the characteristic turnover mass, $M_0$. What causes this change, and why does the turnover occur at about $M_* \approx 10^{10} M_\odot$ at all redshifts?
The slope of the main-sequence

The parameterization of the main sequence we employ in Section 4.5.1 includes a parameter $\gamma$ that we describe as the low stellar mass power-law slope. However, we note that this slope is not derived from an actual power-law fit to the data, but instead represents the power-law slope that the relationship approaches in the very low-mass regime, based on Equation 4.2. This slope is significantly steeper than power-law slopes commonly quoted in the literature, and should not be compared to slopes from power-law fits to data.

For an easier comparison to the existing literature, we derive best-fit power-law relationships, fitting the low mass regime and high mass regime separately. Galaxies less massive than the turnover mass follow a fairly tight power-law relationship of $SFR \propto M^{\beta}$, with $\beta = 0.88 \pm 0.06$. This slope is shallower than $\gamma$ because it includes galaxies in the “turnover region”, where the slope is already starting to flatten. Galaxies more massive than the turnover mass follow a drastically different relationship, with $\beta = 0.27 \pm 0.04$ for $M_* > 10^{10} M_\odot$. A galaxy’s specific star formation rate ($SSFR \equiv SFR/M_*$) can be interpreted as a measure of the efficiency of current star formation as compared to its past average star formation history. The $SSFR$ of massive galaxies is systematically lower than would be expected from an extrapolation of low mass galaxies, suggesting that there may be decreased star formation efficiency in high stellar mass galaxies.

Quenching in High Mass Galaxies

The turnover in the main sequence to lower star formation efficiencies in massive galaxies suggests there is a fundamental change that occurs as galaxies become more massive, as has been predicted in some studies. Galaxy luminosity and mass functions, which measure the brightness and mass distribution of galaxies at various lookback times, show a steep, exponential decline at high stellar masses and high luminosities while retaining a remarkably consistent shape at all redshifts (e.g. Bell et al. 2003; Pozzetti et al. 2010; Ilbert et al. 2013). The lack of large, bright galaxies throughout cosmic time argues for the presence
of a characteristic mass above which a galaxy is likely to have its star formation strongly suppressed or quenched.

In contrast, the dark matter halo mass function from semi-analytic models does not show the same exponential decline, and instead has a much shallower power-law cutoff at much higher masses (Somerville & Primack 1999; Benson et al. 2003), leading to a “pivot mass” above which the ratio of dark matter to light matter increases rapidly (e.g. Leauthaud et al. 2012). At low stellar masses, the stellar to halo mass relation \( M_h \propto M_*^{0.46}; \) Leauthaud et al. 2012 and the dark matter halo growth rates from N-body simulations \( \dot{M}_{\text{halo}} \propto (M_{\text{halo}})^{1.1}; \) Wechsler et al. 2002; McBride et al. 2009; Fakhouri & Ma 2010) suggest a main sequence relationship of \( SFR \propto M_*^{1.04}, \) similar to the slope seen in the main-sequence. The “pivot mass”, above which the stellar-to-halo mass relation deviates from the low stellar mass relationship, appears to evolve to higher \( M_* \) at higher redshifts (Leauthaud et al. 2012), at a rate similar to the possible evolution seen in the main sequence turnover mass, \( M_0. \) In galaxies more massive than the “pivot mass,” the halo mass rises sharply in comparison with stellar mass, suggesting that while massive dark matter haloes appear to continue growing, the galaxies residing in them quench their star formation.

Possible mechanisms for this quenching include structural disruptions or galaxy mergers (Sanders & Mirabel 1996; Hopkins et al. 2006), feedback from accretion onto a supermassive black hole (Springel et al. 2005), gravitational heating of the surrounding intracluster medium (Khochfar & Ostriker 2008), changes in the mode of gas accretion onto galaxies (Kereš et al. 2005; Birnboim et al. 2007; Nelson et al. 2013), or gas removal or strangulation in dense environments (Peng et al. 2010, 2012).

Morphological studies may be key for understanding the star-formation in massive galaxies. Abramson et al. (2014) find that galaxy SFRs are more strongly correlated to disk stellar mass (as opposed to total stellar mass), and that \( SSFR_{\text{disk}} \) is approximately constant with mass. If this is the case, the turnover in the main-sequence could be simply due to growing bulges in the highest mass systems. However, one might expect the turnover to disappear (or become less severe) at high redshifts as galaxies become more disk-dominated.
but this is not seen in the data. Schawinski et al. (2014) find that disk galaxies and elliptical galaxies likely quench their star formation rates through different processes with very different timescales. A galaxy’s physical size may also play a role in quenching, as the surface mass density has been shown to correlate strongly with SSFR (Kauffmann et al. 2003; Franx et al. 2008), and compact star forming galaxies may be on the evolutionary path toward quiescent galaxies (Barro et al. 2014).

Our data suggest that galaxies with high stellar mass ($M_* > 10^{10} M_\odot$) are forming stars at a lower rate than would be expected from extrapolating the trends of low stellar mass galaxies. Finding the possible causes of this “quenching” of star formation is one of the key hurdles for understanding galaxy evolution. The existence of a “turnover mass” hint that the stellar mass of a galaxy plays a crucial role in quenching, possibly related to the “mass quenching” discussed in Peng et al. (2010). Further study is needed to determine the physical mechanism(s) behind quenching.

4.6.2 Increasing SFR with Redshift

From our fits, we find strong evolution in $S_0$, which parameterizes the overall scaling of the $SFR/M_*$ main-sequence with redshift. The scaling of the main sequence has been found in the literature to evolve as $(1 + z)^n$, with the exponent $n$ varying from $2.2 < n < 5$ (Erb et al. 2006; Daddi et al. 2007; Damen et al. 2009; Dunne et al. 2009; Pannella et al. 2009; Karim et al. 2011). The value of $n = 4.12 \pm 0.10$ we measure is among the steeper slopes seen in the literature.

It’s thought that the redshift evolution of the main-sequence normalization is due, at least in part, to increasing gas content in galaxies at earlier cosmic times. However, measuring the gas content in galaxies can be difficult, especially in high redshift systems. Molecular hydrogen is notoriously difficult to detect, so many surveys instead probe the rotational transitions of CO and use locally calibrated CO-to-H$_2$ conversion factors, although this conversion factor may differ in starburst galaxies (Tacconi et al. 2008; Magdis

\footnote{Alternatively, measuring the redshift evolution of the SFR at a constant characteristic mass provides similar results}
et al. 2011; Magnelli et al. 2012). Another method to estimate gas content is to measure the dust mass from far-infrared or submillimeter photometry and convert to gas masses using an assumed gas-to-dust ratio (e.g. Magdis et al. 2012; Santini et al. 2014; Scoville et al. 2014). Magdis et al. (2012) find gas fraction evolves as \((1 + z)^{2.8}\), while recent ALMA observations suggest a steeper evolution of \((1 + z)^{5.9}\) (Scoville et al. 2014). Zahid et al. (2014) study the mass metallicity relationship and infer a much shallower evolution of gas mass \(M_g \propto (1 + z)^{1.35}\). Future studies will be needed to determine if the evolving normalization of the main-sequence can be explained simply by an increasing gas supply in galaxies, or if other explanations such as increased merger rates or increased star formation efficiency are necessary to fully explain the observed evolution.

4.7 Conclusions

Using new far-infrared data from Herschel, we compare direct measurements of unobscured and obscured SFR with various SFR indicators that estimate the obscured SFR from data at shorter wavelengths (usually in optical or UV), and find that the NRK method of Arnouts et al. (2013) provides the most consistent estimate of the far-infrared derived SFR. By combining the SFRs from Herschel, Spitzer, and NRK, we analyze the relationship between SFR and \(M_*\) (commonly referred to as the “star-forming main-sequence”) in 62,521 star-forming galaxies at \(z \leq 1.3\) in the COSMOS field. From our new analysis we find:

- The relationship between SFR and stellar mass does not follow a simple power-law, but flattens to near-constant SFRs at high stellar masses. The shape of the main sequence is roughly constant for all redshifts \(z \leq 1.3\).

- The scaling of the entire star-forming main sequence rises with redshift as \((1 + z)^{4.12 \pm 0.10}\).

- The characteristic turnover mass lies at \(M_0 \approx 10^{10} M_\odot\), with possible evolution toward higher turnover masses at high redshift.

100
• The slope of the low-mass power-law lies between $\gamma = 0.9-1.3$, with possible weak evolution toward steeper slopes at higher redshift.

• A broken power-law fit to galaxies below and above the turnover mass results in $SFR \propto M_*^{0.88\pm0.06}$ below the turnover mass and $SFR \propto M_*^{0.27\pm0.04}$ above the turnover mass.

Our analysis suggests that star-forming galaxies cannot be described by a single power-law relationship between $SFR$ and $M_*$, as had been suggested in many previous studies. Because of the strong effects of dust, direct observations in the FIR are crucial for studying the entire population of star-forming galaxies. In future work we will explore possible causes of the turnover in the main sequence by studying detailed morphology and examining possible feedback mechanisms, and we will extend our analysis to higher redshifts.

4.8 Acknowledgements

D. B. Sanders and C. M. Casey acknowledge the hospitality of the Aspen Center for Physics, which is supported by the National Science Foundation Grant No. PHY-1066293. C. M. Casey would like to acknowledge generous support from a McCue Fellowship through the University of California, Irvine’s Center for Cosmology. KS gratefully acknowledges support from Swiss National Science Foundation Grant PP00P2_138979/1. KS acknowledges support from the National Radio Astronomy Observatory, which is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

COSMOS is based on observations with the NASA/ESA Hubble Space Telescope, obtained at the Space Telescope Science Institute, which is operated by AURA Inc, under NASA contract NAS 5-26555; also based on data collected at: the Subaru Telescope, which is operated by the National Astronomical Observatory of Japan; the XMM-Newton, an ESA science mission with instruments and contributions directly funded by ESA Member States and NASA; the European Southern Observatory, Chile; Kitt Peak National Observatory, Cerro Tololo Inter-American Observatory, and the National Optical
Astronomy Observatory, which are operated by the Association of Universities for Research in Astronomy, Inc. (AURA) under cooperative agreement with the National Science Foundation; the National Radio Astronomy Observatory which is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc; and the Canada-France-Hawaii Telescope operated by the National Research Council of Canada, the Centre National de la Recherche Scientifique de France and the University of Hawaii.

The Dark Cosmology Centre is funded by the Danish National Research Foundation.
References


Ilbert, O., McCracken, H. J., et al. 2013, A&A, 556, A55 [(document), 4.3, 4.3.1, 4.3.3, 4.4.1, 4.1, 4.5.3, 4.6.1]


104


Chapter 5
Summary and Future Work

5.1 Summary

Over the last 7 years, we have done significant research on the properties of infrared luminous galaxies, especially at high redshift. With new instruments, we conducted and analyzed the largest, most complete survey of far-infrared selected galaxies. In addition to a more accurate characterization of this important class of galaxies, we also used our new understanding of dust obscuration to better study galaxy star formation processes during the key epoch of galactic and stellar growth in the universe. Many of these results have been published in peer-reviewed journals.

The main conclusions from our studies are:

- Far-infrared observations ($\geq 100\mu m$) are necessary to accurately characterize the emission from luminous, high redshift galaxies where extrapolations from observations at shorter wavelengths (ie. $24\mu m$) systematically over predict the infrared luminosity (Lee et al. 2010).

- Dust mass and dust temperature both increase with total infrared luminosity (Lee et al. 2013).
- Infrared luminous galaxies have an increasingly larger fraction of AGN at higher luminosities, as demonstrated by X-ray detection fraction (Lee et al. 2010) and SED shape (Lee et al. 2013).

- Far-infrared selected galaxy populations do not follow the $SFR - M_\ast$ relationship seen in studies at optical and mid-IR wavelengths (Lee et al. 2013).

- The NRK method (Arnouts et al. 2013) provides the most accurate optical/UV-based estimate of obscured SFR at low and moderate SFR, but galaxies with high SFR require far-infrared observations for accurate characterization (Lee et al. 2015).

- The relationship between $SFR$ and $M_\ast$ in star-forming galaxies is stellar-mass dependent. At low stellar masses ($M_\ast \lesssim 10^{10} M_\odot$), galaxies follow a power-law relationship of the form $SFR \propto M_\ast^\beta$ with $\beta \sim 0.7$–1.0, while massive galaxies follow a trend with much shallower slopes of $\beta \sim 0.2$–0.3 (Lee et al. 2015).

- The correlation between $SFR$ and $M_\ast$ has a relatively constant shape out to $z < 1.3$, and the normalization of the relationship rises as $(1 + z)^{4.12 \pm 0.1}$ (Lee et al. 2015).

As a result of these studies, we have developed a better understanding of the effects of dust obscuration in the high redshift universe, and in turn a better understanding of how star formation has progressed throughout the history of the universe. These new results also present many new unanswered questions that will require further research. In the following sections we outline some key questions that arise from this work.

5.2 Future Work - AGN in Infrared Galaxies

Many studies have demonstrated a connection between infrared luminous galaxies and the presence of AGN, with AGN fraction generally increasing with greater $L_{IR}$ (Lee et al. 2010; Kartaltepe et al. 2010; Treister et al. 2010; Lee et al. 2013). As infrared luminosity is an excellent tracer of star formation rate, this suggests a connection between AGN growth and the buildup of stellar mass. This connection is further supported by the tight correlation
between central supermassive black hole masses and their host galaxy bulge masses that suggests that AGN and star formation activity may have been concurrent (Magorrian et al. 1998; Ferrarese & Merritt 2000; Gebhardt et al. 2000).

However, while galaxies with high SFRs have a higher probability of containing an actively accreting black hole, there are suggestions that the strength of the AGN is not affected by the SFR. Daddi et al. (2007) find that the AGN luminosities of \( z \approx 2 \) star forming galaxies selected at 24 \( \mu \)m were comparable to the AGN luminosities of Submillimeter Galaxies (\( L_{2-8keV} \sim (1 - 4) \times 10^{43}L_\odot \), Alexander et al. 2005), despite star formation rates that differed by about an order of magnitude.

Questions remain about what is driving the relationship between AGN occurrence rate and infrared luminosity. A simple explanation may be that the same reservoirs of gas that drive star formation are also fueling AGN growth, but this should lead to a correlation between SFR and AGN luminosity, which has not been observed. By combining recent surveys of the COSMOS field by the Chandra X-ray Observatory with our deep Herschel survey, we can accurately study the connection between AGN luminosity and star formation and better understand the physical processes driving this relationship. X-ray observations are the ideal method for measuring AGN luminosity, as it is much easier to disentangle contributions from the AGN from X-ray binaries than in observations of optical spectral lines or mid-infrared colors.

A preliminary study based on stacking Chandra emission of infrared luminous galaxies in the central square degree of COSMOS is provided in Figure 5.1. Although the majority of bins did not have the signal-to-noise needed for significant detections, the upper limits and few detections suggest a trend where the X-ray spectral shapes of infrared luminous galaxies seem to transition from an M82-like spectrum (pure star-formation) to Mrk273-like spectrum (AGN dominated) with increased infrared luminosity and redshift. With newly completed surveys with both Chandra and Herschel, this comparison can be extended to further explore the apparent connection between AGN and star-formation.
5.3 Future Work - Quenching

Our results lead to another major question - what causes the turnover we see in the SFR/$M_*$ relationship? The shallower slope seen for high stellar mass galaxies suggests that, on average, massive galaxies have lower specific star formation rates ($SSFR \equiv SFR/M_*$). SSFR is a measure of the efficiency of current star formation as compared to its past average star formation history, and these low efficiencies suggest that massive galaxies are undergoing a “quenching” phase where active star-forming galaxies shut down their star formation and evolve into red and dead elliptical galaxies.

Such a quenching mechanism has been theorized as necessary to resolve fundamental tensions between prediction of the $\Lambda$CDM universe and key observable galaxy properties. For example, cosmological models that include dark matter halo growth, gas cooling, star
formation, and stellar feedback overproduce extremely luminous galaxies, likely because they are unable to suppress star formation in massive galaxies (Benson et al. 2003; Somerville et al. 2008; Davé et al. 2011). Our new results on the relationship between galaxy SFR and $M_*$ provide the first robust sample of massive galaxies quenching their star formation, and these galaxies can be studied in depth to determine the physical mechanism that is shutting down the star formation.

There are many possible processes by which galaxies may shut down their star formation, and many of them have observable signatures. Stars form in clouds of (predominantly molecular hydrogen) gas, so quenching may occur through a reduction of the galaxy’s available gas supply by either expelling gas from the galaxy or restricting the replenishment of the gas supply from the intergalactic medium (IGM). Gas content is traditionally measured from CO line fluxes, but this is prohibitively time-consuming for large samples and relies on an uncertain CO-to-H$_2$ conversion factor (e.g. Tacconi et al. 2008). A significantly faster measurement can be made by inferring ISM mass from measurements of the optically thin Rayleigh-Jeans tail of infrared emission and assuming a gas-to-dust ratio (e.g. Magdis et al. 2012; Scoville et al. 2014).

Other proposed mechanisms for quenching include feedback from AGN and structural disruptions from events such as major mergers. The well established connection between a galaxy’s bulge mass and the mass of the supermassive black hole at its center (Magorrian et al. 1998) suggests that the buildup of stellar mass and the growth of black holes must be intimately related, possibly due to AGN feedback. The most direct indication of AGN activity in a galaxy is detection of (hard) X-ray emission originating from the hot accretion disk surrounding a supermassive black hole, and recent models suggest that interaction between AGN outflows and host galaxy ISM should produce detectable, spatially extended X-ray emission (e.g. Nims et al. 2014).

As galaxies evolve from star-forming to quiescent, their structure can also change from disk to elliptical, and it has been suggested that galaxy mergers (or some other disruption such as minor mergers or disk instabilities) are the cause of this structural change (Springel...
et al. 2005). Although major mergers commonly trigger bursts of star formation, the starburst phase is generally short lived and quickly followed by a period of quenching that leads to a quiescent galaxy (e.g. Hopkins et al. 2008). Galaxies undergoing significant structural changes can be identified by their irregular morphologies and tidal features, although these can be more difficult to identify at high redshifts ($z \gtrsim 1$; Hung et al. 2014).

Our followup work will identify a robust population of quenching galaxies and study how the gas content, presence of AGN, and morphology evolve based on location with respect to the “main-sequence” relationship in SFR and $M_\star$. With this future work, we will be able to determine the physical mechanism by which massive star-forming galaxies quench their star formation to become quiescent galaxies.
References


