THE INFRARED PROPERTIES OF SOURCES MATCHED IN THE WISE ALL-SKY AND HERSCHEL ATLAS SURVEYS

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We describe the infrared properties of sources detected over $\sim 36$ deg$^2$ of sky in the GAMA 15-hr equatorial field, using data from both the Herschel Astrophysical Terahertz Large-Area Survey (H-ATLAS) and Wide-field Infrared Survey (WISE). With 5$\sigma$ point-source depths of 34 and 0.048 mJy at 250 $\mu$m and 3.4 $\mu$m, respectively, we are able to identify 50.6% of the H-ATLAS sources in the WISE survey, corresponding to a surface density of $\sim 630$ deg$^{-2}$. Approximately two-thirds of these sources have measured spectroscopic or optical/near-IR photometric redshifts of z < 1. For sources with spectroscopic redshifts at z < 0.3, we find a linear correlation between the infrared luminosity at 3.4 $\mu$m and that at 250 $\mu$m, with $\pm 50\%$ scatter over $\sim 1.5$ orders of magnitude in luminosity, $\sim 10^{9}$ - $10^{12}$. By contrast, the matched sources without previously measured redshifts (r $\geq 20.5$) have 250-350 $\mu$m flux density ratios that suggest either high-redshift galaxies (z $\geq 1.5$) or optically faint low-redshift galaxies with unusually low temperatures (T $\leq 20$). Their small 3.4-250 $\mu$m flux ratios favor a high-redshift galaxy population, as only the most actively star-forming galaxies at low redshift (e.g., Arp 220) exhibit comparable flux density ratios. Furthermore, we find a relatively large AGN fraction ($\sim 30\%$) in a 12 $\mu$m flux-limited subsample of H-ATLAS sources, as well as with there being a significant population of high-redshift sources in the no-redshift sample.

Subject headings: surveys – cosmology: observations – galaxies: high-redshift – infrared radiation – galaxies: statistics – galaxies: general
1. INTRODUCTION

The advent of submillimeter astronomy has opened a new window into the Universe, allowing us to probe dusty star-forming galaxies at high redshift, as well as cold dust in nearby galaxies. Along with the recent success of the balloon-borne BLAST experiment (Pascale et al. 2008; Eales et al. 2009), the launch of the Herschel Space Observatory1 (Pilbratt et al. 2010) allows us to probe wavelengths from 55 to 672 \mu m with a spatial resolution of \lesssim 10''

Its largest open-time key project, the Herschel Astrophysical Terahertz Large-Area Survey (H-ATLAS, Eales et al. 2010a), will observe \approx 550 deg$^2$ of sky and detect more than 300,000 galaxies.

Based upon a preliminary cross-identification with the Galaxy and Mass Assembly survey (GAMA, Driver et al. 2011) and Sloan Digital Sky Survey (SDSS, Abazajian et al. 2009), \approx 50\% of the sources detected in the H-ATLAS survey are at $z < 1$ (Smith et al. 2011). In addition, an analysis of the FIR colors of the remaining H-ATLAS sources with flux densities above 35 mJy at 350 \mu m and > 3\sigma detections at 250 \mu m and 500 \mu m suggests an average redshift of $z \approx 2$ (Ambland et al. 2010; Lapi et al. 2011).

Another method of constraining the redshift distribution of FIR-selected sources is to look for counterparts in the near and mid infrared (NIR and MIR). Fleuren et al. (in prep) have performed source matching to survey data from the VISTA Kilo-degree Infrared Galaxy survey (VIKING, Sutherland et al., in prep), but these data only extend to \approx 2 \mu m. Starting in December 2009, the Wide-field Infrared Survey Explorer2 (WISE, Wright et al. 2010) began its mission to observe the entire sky in four bands, ranging from 3.4 to 22 \mu m, at \lesssim 12'' resolution. Following the first public data release in April 2011, \approx 24,000 deg$^2$ of IR images and source catalogs became available to the public, including 36 deg$^2$ of sky in the equatorial plane covered by the H-ATLAS survey.

The purpose of this letter is to describe the infrared properties of identified WISE counterparts to H-ATLAS sources within the GAMA 15 hr field (G15). Throughout we will assume a concordance cosmology with $H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.27$, and $\Omega_{\Lambda} = 0.73$ (Spergel et al. 2007). In a subsequent paper, we will report WISE cross-identifications over the entire H-ATLAS area and perform spectral energy distribution (SED) fits to the matched sources.

2. DATA AND METHODOLOGY

Herschel observations of the G15 field include imaging data at 250, 350, and 500 \mu m from the SPIRE instrument, with respective beam FWHM of 18''1, 25''2, and 36''6 (Griffin et al. 2010), as well as 100 and 160 \mu m imaging from the PACS instrument (Poglitsch et al. 2010). The field subtends approximately 12'' in right ascension and 3'' in declination and is centered on the equatorial plane at $\alpha = 14h30m$. The H-ATLAS G15 source catalogue (Dunne et al., in prep) is constructed using the same method as the Science Demonstration Phase catalogue (Rigby et al. 2011). It contains 27,481 sources detected at > 5\sigma in any of the three SPIRE bands and reaches point-source depths of 34, 40, and 44 mJy at 250, 350, and 500 \mu m, respectively.

The WISE first public data release contains four-band coverage of the entire G15 field to 5\sigma point-source depths of 0.048, 0.10, 0.73, and 5.9 mJy at 3.4, 4.6, 12, and 22 \mu m. The angular resolution in these bands is 6''1, 6''4, 6''5, and 12''0, respectively (Wright et al. 2010). There are \approx 240,000 WISE sources within G15 detected at > 7\sigma in at least one of the four WISE bands, corresponding to \approx 0.14 WISE sources per 10''-radius aperture. In the WISE preliminary release catalog, close pairs of sources are not deblended for separations \lesssim 9'', so when a background or foreground source appears near an H-ATLAS source position, it will often be blended with the true counterpart.

In addition to the infrared data from WISE and H-ATLAS, the G15 region has spectroscopic redshifts from the GAMA survey ($r \lesssim 19.4$, Driver et al. 2011), and photometric redshifts obtained using optical/NIR photometry from SDSS, VIKING, and the UK Infrared Deep Sky Survey Large Area Survey (UKIDSS-LAS, Lawrence et al. 2007). Of the 27,481 H-ATLAS sources in the region, 16\% have reliable spectroscopic redshifts and 39\% have photometric redshifts.

As a result of the high space density of 3.4 \mu m sources, a naive matching to the H-ATLAS source positions will result in a non-negligible number of misidentifications. A significant fraction of these misidentifications will be foreground stars that are blue in all WISE bands and undetectable in H-ATLAS, so we can reduce the contamination rate of our matched catalog by considering only WISE sources with $[3.4] - [4.6] > 0$. The magnitude distribution of all background/foreground WISE sources is such that \approx 20\% are bluer than this limit, as compared to < 1\% of sources within 10'' of an H-ATLAS position.

To estimate the fraction of H-ATLAS sources with detectable counterparts in the remainder of the WISE source catalog, we use the method of Fleuren et al., in prep, where it is shown that by counting non-matches within a fixed distance from the H-ATLAS positions, we can estimate the detection rate,

$$Q_0 = 1 - \frac{S}{B},$$

where $S$ is the fraction of unmatched positions in the H-ATLAS catalog and $B$ is the fraction of unmatched random positions. This expression holds under the condition that there are a negligible number of true WISE matches outside of the matching radius. Matching all WISE sources within 10'' (within which we expect > 99\% of the true matches to lie) and using 10$^5$ random positions within the G15 field, we find $Q_0 = 0.632 \pm 0.004$. This is larger than the value found in the SDSS galaxy catalog ($Q_0 = 0.583$, Smith et al. 2011), but smaller than in the VIKING $Ks$ band ($Q_0 = 0.75$, Fleuren et al., in prep). By contrast, we find $Q_0 = 0.012 \pm 0.002$ within the subset of WISE sources with $[3.4] - [4.6] < 0$, suggesting that this color cut was effective in removing stars.

In Fig. 1, we use Eq. 1 to estimate the IR detection rate as a function of FIR flux density. We find that WISE 3.4 \mu m detection rates are > 95\% for sources brighter
Sources in both H-ATLAS and WISE

Fig. 1.— NIR and MIR detection rates plotted as a function of limiting FIR flux density at 250 µm (solid), 350 µm (dashed), and 500 µm (dotted). Detection rates are shown for 3.4 µm (upper left panel), 4.6 µm (upper right), 12 µm (lower left), and 22 µm (lower right) sources, where the corresponding 5σ detection limits are 0.06, 0.9, and 3.6 mJy, respectively. Note that the large sky density of 3.4 µm sources can lead to ambiguity in the identification of some sources, so identification rates are typically ~10-20% lower than the corresponding detection rates.

than 100 mJy at 250 µm. The vast majority of these sources (78%) have measured spectroscopic or photometric redshifts < 0.5, suggesting that the low-redshift mode of star-forming galaxies dominates sub-mm sources above this flux density. Below this FIR flux density, the NIR and MIR detection rates drop rapidly as the high-redshift mode accounts for an increasing fraction of the sub-mm sources (see Fig. 2).

By contrast, ~50% of sources brighter than 100 mJy at 500 µm are expected to be lensed z > 1 galaxies (Negrello et al. 2010; Hopwood et al. 2011). Of the 46 such sources in the G15 region, ~20% are undetected at 12 and 22 µm, most likely because the 500 µm bandpass shifts higher in the blackbody curve at high redshift, while the rest-frame MIR flux density declines blueward of 22 µm (e.g., Rieke et al. 2000).

The identification of individual NIR and MIR counterparts is more subtle, as we want to eliminate as many of the false matches as possible. Here, we use the likelihood ratio technique of Sutherland & Sanders (1992), which was implemented for the H-ATLAS survey in Smith et al. (2011, hereafter S11). Because >99.9% of sources in the WISE catalog are detected at 3.4 µm at >7σ, we use this band for source identification. The likelihood that a given WISE source is a counterpart to an H-ATLAS source is a function of the radial probability distribution, \( f(r) \), the 3.4 µm magnitude distribution of non-counterparts, \( n(m) \), and the 3.4 µm magnitude distribution of detected H-ATLAS counterparts, \( q(m) \):

\[
L = \frac{q(m)f(r)}{n(m)},
\]

where \( f(r) \) is given by

\[
f(r) = \frac{1}{2\sigma_{\text{pos}}^2} \exp \left( -\frac{r^2}{2\sigma_{\text{pos}}^2} \right).
\]

where \( \sigma_{\text{pos}} = 0.655 \frac{\text{FWHM}}{\text{SNR}} \),

\[
R_j = \frac{L_j}{\sum_i L_i + (1 - Q_0)}.
\]

We consider any 3.4 µm source with \( R > 0.8 \) to be a reliable counterpart. After performing this procedure separately for WISE sources with star- and galaxy-like [3.4] - [4.6] colors, we obtain a combined total of 13,898 WISE counterparts, or 50.6±0.4% of the H-ATLAS catalog. The expected number of false matches can be obtained with

\[
N_{\text{falseID}} = \sum_i (1 - R_i).
\]
FIR flux density ratio distribution for 311 H-ATLAS sources with WISE identifications, but without measured redshifts. Colored points indicate the median redshift of a set of modified blackbody models with temperatures uniformly distributed between 10 and 60 K and emissivity parameters between 0 and 2. Dashed lines indicate the median flux density ratios of the sources lacking redshifts. The majority of the sources without redshifts appear to be at $z \sim 2$. Inset: Combined distribution of spectroscopic and photometric redshifts for H-ATLAS sources with detections at 3.4 $\mu$m (solid histogram), 12 $\mu$m (dashed), and 22 $\mu$m (hatched). There are 73 sources at $z > 1$ not shown.

We estimate that there are 369 false identifications in our sample, corresponding to a contamination rate of 2.7%. The majority of our IDs have galaxy-like colors, but we were able to identify 14 objects with star-like colors ($[3.4] - [4.6] < 0$) that weren’t already identified as galaxies with SDSS matching. This corresponds to an upper limit of 0.05% for the fraction of H-ATLAS sources identified as stars and detected in WISE.

Comparing the individual WISE identifications to SDSS cross-identifications, we find that 84.7% of the 10,709 G15 H-ATLAS sources with $R > 0.8$ SDSS identifications also had $R > 0.8$ WISE identifications. The median separation between the WISE and SDSS sources is 0.6", consistent with the astrometric uncertainties in the current version of the WISE catalog. In addition, ~6% of these sources have separations >3", consistent with the expected contamination rates of the WISE (~3%) and SDSS (~5%) matched samples.

3. DEMOGRAPHICS

The redshift distribution of 250 $\mu$m-selected sources is likely bimodal, with populations of both moderately-star-forming galaxies at $z < 1$ and high-redshift starburst galaxies at $z \sim 2$ (Smith et al. 2011; Lapin et al. 2011). Because the latter are typically faint in the observed-frame optical and UV, the vast majority of objects with measured spectroscopic or photometric redshifts are in the low-redshift mode. Of the H-ATLAS sources with spectroscopic and photometric redshifts (see the inset of Fig. 3), we successfully identify 85.6% in WISE.

Although most of the WISE identifications with known redshifts are at $z < 0.8$ (>98%), such a sample is biased toward low redshift because redshift measurements require detectable flux in the UV, optical, or near-infrared. For the remaining sources, we can estimate redshifts using their FIR flux density ratios (e.g., Amblard et al. 2010; Schulz et al. 2010), which give an indication of the location of the peak of the FIR dust emission. In Fig. 3, we compare the SPIRE colors of our matched catalog to a suite of 10$^6$ modified blackbody spectral energy distributions (including uncertainties) with temperatures uniformly distributed between 10 and 60 K and emissivity parameters between 0 and 2 (Amblard et al. 2010). We indicate on the plot the median flux density ratios of the 4,677 H-ATLAS sources with WISE identifications but no redshifts (“no-redshift” sample, dashed lines), as well as the individual flux density ratios of 311 such sources with $>3\sigma$ detections in all three SPIRE bands.

The no-redshift sample has median FIR colors suggesting $z \sim 2$, while the subset with three-band SPIRE detections may have even higher redshifts, perhaps as large as $z \sim 3.5$. The redshifts derived in this way are highly uncertain, as redshift is degenerate with dust temperature in the FIR and it is possible that these galaxies have typical dust temperatures different than 35 K. However, in order for the no-redshift sample to be at $z \sim 0$, they would need to have very cold dust temperatures ($T \sim 12$ K) in addition to being very faint in the optical ($r \gtrsim 20.5$). Although temperatures as low as 10 K have been seen in H-ATLAS galaxies at $z < 1$, $T \sim 25 - 30$ K is more typical (Dye et al. 2010).

Further evidence that the no-redshift sources are at $z > 0$ can be found in the 3.4-250 $\mu$m ratios (see Fig. 2). H-ATLAS sources with GAMA redshifts have NIR-FIR flux density ratios that decrease from $\sim 0.009$ at $z \sim 0$ to $\sim 0.006$ at $z \sim 0.35$. This trend, which continues toward higher redshift, is due primarily to the larger k-correction at 35 K than at 250 $\mu$m (e.g., Rieke et al. 2009). The median flux density ratio for the no-redshift sources, by comparison, is 0.0023. Although low-redshift galaxies will occasionally exhibit such small NIR-FIR flux density ratios – Arp 220, for example, has $f_{3.4}/f_{250} = 0.0019$ – such objects are rare, actively star-forming, and unlikely to have dust temperatures as small as $\sim 15$ K.

We can shed even further light on the properties of the no-redshift sample by examining their position in WISE color space (see Fig. 4). The technique is similar to those developed for a set of IRAC filters at comparable wavelengths (Sajina et al. 2005; Stern et al. 2005). It was demonstrated that the diagram can be divided into stars and early-type galaxies (lower left corner, $[4.6] - [12] \lesssim 2.2$, star-forming galaxies (lower right corner), and active galactic nuclei (AGNs), where AGNs are selected largely based on their power-law emission in the NIR and MIR. This was adapted for WISE by Jarrett et al. (2011),

$$[4.6] - [12] > 2.2$$

$$[4.6] - [12] < 4.2$$


$$[3.4] - [4.6] > 0.1([4.6] - [12]) + 0.38$$

Of the 4,959 H-ATLAS sources with WISE identifications, $z < 0.5$, and detections in 3.4, 4.6, and 12 $\mu$m, the majority are star-forming galaxies, with $< 0.2%$ main sequence stars (which is consistent with the SDSS/H-ATLAS matching done by Thompson et al. 2010), and a small AGN fraction (0.057),
Sources in both H-ATLAS and WISE

4. FIR-NIR PROPERTIES

Emission from dust in the FIR is often used as an indicator of the total star formation rate in galaxies (e.g., Kennicutt 1998), under the assumption that most of the dust heating is provided by young stars and that the star-forming regions are optically thick. The 250 µm bandpass samples the cooler dust emission, which can arise from both star-forming clouds and diffuse regions in the ISM (e.g., Eales et al. 2010b; Dunne et al. 2011). By contrast, 3.4 µm emission is dominated by stellar sources and is a probe of the stellar mass for galaxies without a strong AGN contribution (e.g., Stern et al. 2005).

In Fig. 5, we plot 3.4 µm luminosity as a function of 250 µm luminosity for H-ATLAS sources with spectroscopic redshifts, 0.05 < z < 0.3. We k-correct 3.4 µm using a power law interpolation of the [3.4] - [4.6] color. For the 250 µm flux densities, the majority of the galaxies in our sample do not have sufficient FIR flux density to obtain reliable dust temperatures, as is needed for a proper k correction. Instead, we use the median dust temperature of 26 K found by Dye et al. (2010) using PACS and SPIRE data from the H-ATLAS SDP of 1,346 0.1 < z < 0.5 sources. Although the r < 19.4 limit of the GAMA spectroscopic survey restricts the range of luminosities that can appear on the plot, we estimate that GAMA misses only ~5% of matched z < 0.3 galaxies based upon the deeper (r < 20.5) subsample of H-ATLAS galaxies with photometric redshifts.

We find that the majority of the IR-color-selected AGN (red points) lie above the relationship for star-forming galaxies, as L_{3.4} will contain a non-negligible contribution from hot dust emitting near the central black hole in addition to emission from low-mass stars. However, if we exclude AGNs, we find an approximately linear correlation, with a best-fit power law index, $\alpha = 0.98^{+0.05}_{-0.03}$. The quoted systematic uncertainties on the power law index were determined by allowing for a range of possible dust temperatures, 18 < T < 34 K, when performing 250 µm k-corrections. The intrinsic scatter about this relationship is 0.18 ± 0.01 dex, or ~50%.

The existence of a linear correlation between L_{250} and L_{3.4} across one and a half decades in luminosity suggests a close relationship between the cold dust probed by the FIR and the stellar mass probed by the NIR. Previous indications with Herschel have shown the 250 µm luminosity density to tightly correlate with both the 24 µm luminosity density, a star formation rate indicator, and the total infrared luminosity (Elbaz et al. 2010). This fact, coupled with a linear correlation between stellar mass and star formation rate for the general star-forming galaxy population (Daddi et al. 2007; Elbaz et al. 2007; Noeske et al. 2007; Donoso et al., in prep), suggests that the majority of the low-redshift H-ATLAS sources are actually "normal" star-forming galaxies.

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REFERENCES

—. 2010a, PASP, 122, 499
Lapi, A. et al. 2011, ArXiv e-prints