GOODS-HERSHEL: SEPARATING HIGH-REDSHIFT ACTIVE GALACTIC NUCLEI AND STAR-FORMING GALAXIES USING INFRARED COLOR DIAGNOSTICS

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Received 2012 July 1; accepted 2012 December 12; published 2013 January 16

ABSTRACT

We have compiled a large sample of 151 high-redshift \((z = 0.5–4)\) galaxies selected at \(24 \mu \text{m} (S_{24} > 100 \mu \text{Jy})\) in the GOODS-N and ECDFS fields for which we have deep Spitzer IRS spectroscopy, allowing us to decompose the mid-infrared spectrum into contributions from star formation and activity in the galactic nuclei. In addition, we have a wealth of photometric data from Spitzer IRAC/MIPS and Herschel PACS/SPIRE. We explore how effective different infrared color combinations are at separating our mid-IR spectroscopically determined active galactic nuclei from our star-forming galaxies. We look in depth at existing IRAC color diagnostics, and we explore new color–color diagnostics combining mid-IR, far-IR, and near-IR photometry, since these combinations provide the most detail about the shape of a source’s IR spectrum. An added benefit of using a color that combines far-IR and mid-IR photometry is that it is indicative of the power source driving the IR luminosity. For our data set, the optimal color selections are \(S_{50}/S_{24}\) versus \(S_{8}/S_{1.6}\) and \(S_{100}/S_{24}\) versus \(S_{8}/S_{1.6}\); both diagnostics have \(\sim 10\%\) contamination rate in the regions occupied primarily by star-forming galaxies and active galactic nuclei, respectively. Based on the low contamination rate, these two new IR color–color diagnostics are ideal for estimating both the mid-IR power source of a galaxy when spectroscopy is unavailable and the dominant power source contributing to the IR luminosity. In the absence of far-IR data, we present color diagnostics using the Wide-field Infrared Survey Explorer mid-IR bands which can efficiently select out high-z \((z \sim 2)\) star-forming galaxies.

Key words: dust, extinction – galaxies: high-redshift – galaxies: star formation – infrared: galaxies

Online-only material: color figures

1. INTRODUCTION

In the current narrative of galaxy evolution, star formation (SF) and the growth of supermassive black holes are intertwined. The star formation rate density of the universe peaks from \(z \sim 1\) to 3 (e.g., Bouwens et al. 2009; Magnelli et al. 2011; Murphy et al. 2011), an epoch in which the black holes within the center of massive galaxies are simultaneously building up their mass (Wall et al. 2005; Kelly et al. 2010). There is compelling evidence that the growth of black holes and the buildup of stellar mass is linked, though the processes that regulate, and ultimately quench, the simultaneous growth of the stellar mass and black hole are not yet fully disentangled (e.g., Mullaney et al. 2012).

To study the properties of active galactic nuclei (AGNs) and star-forming galaxies at \(z \sim 1–3\), when the star formation rate in the most massive galaxies begins to decline, it is necessary to first identify systems likely harboring an AGN. Because AGNs are much more luminous in the X-ray than star-forming galaxies, X-ray detection provides one of the best means of identifying an AGN (e.g., Alexander et al. 2003). Deep field surveys with the Chandra X-Ray Observatory have exposed an AGN population out to \(z \sim 5\) (e.g., Brandt et al. 2001; Giacconi et al. 2002). However, detailed X-ray spectral analysis shows that the majority of sources are obscured by gas and dust (see Brandt & Hasinger 2005 for a review), and there is likely a sizeable fraction of AGNs that remain undetected by Chandra surveys, as evidenced by the fact that nearly half of the X-ray background is unresolved at >6 keV (Worsley et al. 2005), and the ratio of observed obscured to unobscured AGNs at high redshifts is lower than what is found for comparably luminous AGNs in the local universe (e.g., Treister & Urry 2005).

Due to the incompleteness of surveys conducted at X-ray wavelengths, we must employ alternative methods insensitive to dust obscuration to identify the presence of an AGN. The infrared portion of the spectral energy distribution (SED) shows clear signs of both AGN and SF activity. Based on the presence of polycyclic aromatic hydrocarbons (PAH) and continuum thermal dust emission, mid-infrared spectra can be decomposed into the relative contributions of SF and AGN activity (e.g., Laurent et al. 2000; Armus et al. 2007; Sajina et al. 2011).
In Section 4, we present new color diagnostics based on combining this sample. In Section 3, we explore the efficacy of existing individual sources, and the composite SEDs we create from details of our sample, the mid-IR spectral decomposition of We explore different combinations of colors using both the to select out AGN candidates when spectroscopy is unavailable. Due to AGN signatures from the near-IR to the far-IR, infrared color-selection techniques are a promising way to select out AGNs missed by X-ray surveys, or when X-ray data are unavailable.

In this work, we explore the IR color space for a sample of 151 high-redshift luminous infrared galaxies (LIRGs, $L_{\text{IR}} = 10^{11} - 10^{12} L_\odot$) and ultra-luminous infrared galaxies (ULIRGs, $L_{\text{IR}} > 10^{12} L_\odot$) at high redshift ($z \sim 0.5 - 3.5$) with deep Spitzer mid-IR spectroscopy and a suite of multiwavelength photometry spanning 3.6–500 μm. Several studies have explored using Spitzer IRAC colors as a means to separate AGNs (Lacy et al. 2004; Stern et al. 2005; Donley et al. 2012). For the first time, we explore these various diagnostics using a sample of mid-IR spectroscopically determined AGN and SF galaxies. In light of the emerging Wide-field Infrared Survey Explorer (WISE) photometry, we also discuss how well mid-IR diagnostics separate our spectroscopic AGN and SF sources. The focus of the paper, however, lies in combining near-, mid-, and far-IR photometry to distinguish our AGNs from the SF galaxies. The far-IR is tracing the bulk of the IR luminosity, and if a galaxy’s mid-IR power source is also affecting the far-IR, we expect that combining both portions of the spectrum will be a useful diagnostic.

We build on a previous paper (Kirkpatrick et al. 2012, hereafter Paper I) in which we separate our sample into AGN and SF dominated, based on mid-IR spectral decomposition, and analyze the average IR SEDs of each, including mid-IR spectral features, IR luminosity, and dust temperatures. We have spectroscopically determined AGN and SF galaxies. In light of the emerging Wide-field Infrared Survey Explorer (WISE) photometry, we also discuss how well mid-IR diagnostics separate our spectroscopic AGN and SF sources. The focus of the paper, however, lies in combining near-, mid-, and far-IR photometry to distinguish our AGNs from the SF galaxies. The far-IR is tracing the bulk of the IR luminosity, and if a galaxy’s mid-IR power source is also affecting the far-IR, we expect that combining both portions of the spectrum will be a useful diagnostic.

We perform spectral decomposition using a variety of colors to separate AGNs from the composite SEDs, to determine color combinations that separate AGNs from SF galaxies. The paper is laid out as follows: in Section 2, we describe details of our sample, the mid-IR spectral decomposition of individual sources, and the composite SEDs we create from this sample. In Section 3, we explore the efficacy of existing IRAC color–selection techniques for high-redshift sources. In Section 4, we present new color diagnostics based on combining photometry from the Spitzer Space Telescope and the Herschel Space Observatory. We apply our new diagnostics to the broader Great Observatories Origins Deep Survey North (GOODS-N) and Extended Chandra Deep Field Survey (ECDFS) fields in Section 5, and we end with our conclusions in Section 6. Throughout this paper, we assume a standard cosmology with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.3$, and $\Omega_{\Lambda} = 0.7$.

2. DATA

A full description of our sample and the composite SEDs we create from it is given in Paper I. Here, we summarize the main details and results.

2.1. Multiwavelength Data

Our sample consists of 151 high-redshift galaxies from the GOODS-N and ECDFS fields. We include all sources in these fields that were observed with the Spitzer IRS. While this sample contains a diverse range of sources depending on the goals of each individual observing program, the overriding selection criteria is that each source must be detected at 24 μm with a flux of $5S_\nu > 100$ Jy, since anything fainter will not be observable with the IRS in less than 10 hr. More details on this database of IRS sources in GOODS-N and ECDFS can be found in our data paper (A. Pope et al. 2013, in preparation).

The GOODS fields have been extensively surveyed and are rich in deep multiwavelength data including: ground-based imaging in the near-IR (J and K bands) from VLT/ISAAC (Retzlaff et al. 2010) and CFHT/WIRCam (Wang et al. 2010; Lin et al. 2012); Chandra 2 Ms X-ray observations (Alexander et al. 2003; Luo et al. 2008); 3.6, 4.5, 5.8, 8.0 μm from the Infrared Array Camera (IRAC) on Spitzer; IRS peak-up observations at 16 μm (Teplitz et al. 2011) and MIPS imaging at 24 and 70 μm (Magnelli et al. 2011). Recently, GOODS-N and GOODS-S have been surveyed with the GOODS-Herschel Open Time Key Program (P.I. David Elbaz; Elbaz et al. 2011) using both the PACS and SPIRE instruments providing deep photometry at five far-IR wavelengths: 100, 160, 250, 350, and 500 μm. For the present study, we combine space-based imaging from Spitzer and Herschel to obtain 12 photometric bandwidths spanning the near-IR to the far-IR.

For sources lacking a detection at the Herschel wavelengths, we extract a measurement of the flux density and associated uncertainty for each source directly from our images. The images are in units of mJy beam$^{-1}$, so we use the 24 μm prior positions to find the appropriate pixels for each galaxy. We do not take a measurement when a source looks too blended on the image itself. In Paper I, we present complete Herschel photometry for our IRS sources, as well as indicating which sources have measurements and which have detections at the Herschel wavelengths.

We perform spectral decomposition of the Spitzer IRS mid-IR spectrum for each source in order to disentangle the AGN and SF components. We follow the technique outlined in detail in Pope et al. (2008) which we summarize here. We fit the individual spectra with a model comprised of three components: (1) The SF component is represented by either the local starburst composite of Brandl et al. (2006) or simply the mid-IR spectrum of the prototypical starburst M82 (Förster Schreiber et al. 2003)—with the signal-to-noise ratio, wavelength coverage and spectral resolution of our high-redshift spectra both give equally good fits to the SF component of our galaxies. (2) The AGN component is determined by fitting a pure power law with the slope and normalization as free parameters. (3) An extinction curve from the Draine et al. (2003) dust models is applied to the AGN component. The extinction curve is not monotonic in wavelength and contains silicate absorption features, the most notable for our wavelength range being at 9.7 μm. We fit all three components simultaneously and integrate under the PAH and continuum components to determine the fraction of the mid-IR luminosity (∼5–12 μm) from SF and AGN activity, respectively. For each source, we quantify the strength of the AGN in terms of the percentage of the total mid-IR luminosity coming from the AGN continuum component. Based on this mid-IR spectral decomposition, we find that 38 (25%) out of our sample of 151 galaxies are dominated (>50% of luminosity) in the mid-IR by an AGN.
Diagnostic SF AGN SF Region AGN Region

| Subsample                     | No. of Sources | Median Redshift | $L_{IR}$ (10$^2$ L$_\odot$) | Median $S_{24}$ (mJy) | Median $S_{100}$ (mJy) | Median $S_{8}$ (mJy) |
|-------------------------------|----------------|----------------|-----------------------------|-----------------------|-----------------------|---------------------|
| $z \sim 1$ SF galaxies        | 69             | (39)           | 1.0 (0.9) [0.8, 1.0]        | 0.42 ± 0.17           | 370 [260, 570]        | 7.9 [4.8, 14.7]     |
| $z \sim 2$ SF galaxies        | 44             | (30)           | 1.9 (1.9) [1.8, 2.1]        | 2.00 ± 0.71           | 270 [220, 370]        | 5.2 [1.6, 5.0]      |
| Silicate AGNs                 | 22             | (17)           | 1.9 (1.7) [1.6, 2.0]        | 1.65 ± 0.54           | 470 [250, 860]        | 5.3 [3.0, 10.2]     |
| Featureless AGNs              | 12             | (9)            | 1.2 (1.1) [0.6, 1.6]        | 0.76 ± 0.07           | 1520 [1240, 2300]     | 9.5 [4.0, 11.7]     |

Notes. We list the upper and lower quartile values in brackets next to each calculated median.

a We list the number of sources in each subsample that are used to create the composite SEDs in parentheses. We do not include sources with an incomplete IR SED when creating the composites to avoid biasing our results (see Section 2.3).

b Calculate by integrating under the composite SEDs from 8 to 1000 µm. See Paper I for details.

c Observed frame fluxes.

| Subsample | Median SEDs |
|-----------|-------------|
| SF        |             |
| AGN       |             |

### 2.2. Galaxy Classifications

To more thoroughly compare the mid-IR spectral properties and full IR SEDs within our sample, we divide our sample into four primary subsamples based on the results of the mid-IR spectral decomposition. First, each galaxy is classified as either SF or AGN dominated based on having $<50\%$ and $>50\%$ AGN contribution in the mid-IR, respectively. We further divide the SF galaxies into two bins: $z \sim 1$ ($<z < 1.5$) and $z \sim 2$ ($z > 1.5$). The AGN sources are likewise separated into two bins: those with measurable 9.7 µm silicate absorption (hereafter referred to as silicate AGNs) and those without (hereafter referred to as featureless AGNs). We are unable to further classify four AGN sources as they lack spectral coverage in the relevant range (9–100 µm) to determine whether they exhibit silicate absorption. We refer to these as unclassifiable AGNs in the relevant figures. Our four primary subsamples are listed in Table 1 along with their median redshifts and observed frame median 24, 100, and 8 µm flux densities.

While the majority of our sources are classified as SF dominated based on the mid-IR spectra have a negligible ($<20\%$) contribution from an AGN, the AGN-dominated sources exhibit varying degrees of concurrent SF activity. The featureless AGNs (lacking silicate absorption) primarily have a very strong AGN continuum accounting for $80\%$–$100\%$ of the mid-IR emission, whereas the silicate AGNs have a more uniform distribution of AGN fraction ($50\%$–$100\%$) with some silicate AGNs also having weak PAH features.

### 2.3. Composite SEDs

To assess the average properties of our primary four subsamples of galaxies (due to the small number, we do not examine the unclassifiable AGNs in detail), we created composite SEDs from 0.3 to 600 µm rest-frame by combining data from ground-based near-IR; Spitzer IRAC, IRS, and MIPS (24 µm, 70 µm); Herschel PACS and SPIRE. We reject any source with less than three measurements or detections in the far-IR bandwidths, or any source without mid-IR data in the range 6.4–7.5 µm, as this is the range used to normalize the individual SEDs. After normalization, we stacked flux densities in bin sizes of $\sim0.1$ µm below 20 µm. Above 20 µm, we fit all data points with a two-temperature modified blackbody. Full details of these composites are found in Paper I. The composites are shown in Figure 1 with each composite offset on the y-axis to allow for easier comparisons. Composite SEDs are publicly available.

The two SF composites are remarkably similar in shape and have most emission from cold dust. The featureless AGN composite is nearly a pure power law until $\sim20$ µm, and then is relatively flat from $\sim20$ to 100 µm. The silicate AGN SED is a power law in the near-IR, has weak PAH features and silicate absorption at 9.7 µm, has warm dust emission around 20 µm, and has a cold dust component peaking at the same wavelengths as the SF SEDs. The difference in shapes between the two AGN SEDs and the SF SEDs suggests that IR color diagnostics could be useful for separating AGNs from SF galaxies.

Figure 1. Composite SEDs (and associated uncertainties) for each of our subsamples (see Table 1) created by stacking photometry and spectroscopy in the near- and mid-IR and fitting a two-temperature model to the far-IR. The composites have been offset to allow for easy comparison. The SF templates lack uncertainties in the range 18–30 µm as we lacked data in this wavelength range, and so we interpolate between the mid-IR and far-IR portions of the spectra. Composite SEDs are publicly available.

(A color version of this figure is available in the online journal.)

13 http://www.astro.umass.edu/~pope/Kirkpatrick2012/
Figure 2. Color–color diagnostics from Stern et al. (2005; left panel) and Lacy et al. (2004; middle panel) for selecting AGN-dominated sources (shaded regions). Our SF galaxies separate nicely with redshift ($z < 1.5$ are the filled green circles while $z > 1.5$ are plotted as the open green circles). The AGN sources do not separate in these color–color spaces with redshift and thus are only plotted according to whether they possess a 9.7 $\mu$m absorption feature (open blue squares) or not (filled blue triangles). The four AGNs we were unable to classify as they lacked spectral coverage at 9.7 $\mu$m are plotted as the blue crosses. Overplotted are the redshift tracks calculated from our composite SEDs for $z \sim 2$ SF galaxies (purple) and $z \sim 1$ SF galaxies (red). In the left panel, the $z \sim 1$ SF SED and $z \sim 2$ SF SED diverge around $z \sim 1$ due to the difference in the strength of portion of the stellar bump traced by the 3.6 $\mu$m filter. As the two AGN composites occupy the same region of color space for both the left and middle panels, we only plot the redshift track of the featureless AGN composite SED (in pink) on the left and the track for the silicate absorption AGN (orange) in the middle. The right panel shows the effective wavelengths of the four IRAC bands at different redshifts on each of our composite SEDs, demonstrating that at high redshift these colors sample the stellar bump region.

(A color version of this figure is available in the online journal.)

3. IRAC COLOR–COLOR DIAGNOSTICS

Some of the most well used IR color diagnostics for separating AGN and SF galaxies are presented in Lacy et al. (2004) and Stern et al. (2005) and utilize IRAC colors. The motivation behind an IRAC selection technique is that, at these wavelengths, luminous AGNs should have a monotonically increasing SED, and these power-law colors will separate AGNs from SF galaxies in color space. With our high-redshift photometry and spectroscopy, we are able to apply these diagnostics to a large sample of mid-IR spectroscopically determined AGN and SF galaxies. Lacy et al. (2004) and Stern et al. (2005) define IRAC color–color regions to separate AGNs based on large surveys of low-redshift ($z \lesssim 0.7$) galaxies. As we move to higher redshift ($z \sim 2$), the IRAC bandwidths begin to probe the stellar bump; our composite AGN and SF SEDs exhibit different shapes in the $\lambda < 4 \mu$m region of the spectrum, indicating that IRAC color diagnostics might also be useful at higher redshift. We apply the diagnostics of Stern et al. (2005) and Lacy et al. (2004) to our sample (Figure 2). Sources in our sample that we determined through mid-IR spectral decomposition to be dominated by an AGN (>50%) in the mid-IR are plotted in blue (see the online version for color figures), and sources dominated by star formation are plotted in green.

In the left panel of Figure 2, we plot our sources in the IRAC color–color space defined in Stern et al. (2005) with the gray shaded region being the area defined as AGN dominated by the authors. Our SF sources separate cleanly according to redshift and largely avoid the gray shaded region. We have also overplotted the redshift tracks of our $z \sim 1$ SF composite SED and our $z \sim 2$ SF composite SED. We calculate the redshift tracks of each of our composite SEDs by convolving the SEDs with the IRAC bandpass filters (and MIPS, PACS, SPIRE, and WISE filters in Section 4) at the appropriate wavelengths for a given redshift. The convolution acts to smooth out much of the noise in our spectra as the individual filters span a fairly large wavelength range. The $z \sim 2$ SF track contaminates the AGN region around $z \sim 1$, and in fact, all of the $z \sim 1$ SF galaxies (green filled circles) occupying the shaded region have a redshift between 1 and 1.5. The divergence of the two SF tracks around $z \sim 1$ is due to the fact that the 3.6 $\mu$m filter is tracing the bluest portion of the stellar bump, which has differing strengths relative to the other IRAC filters for the two SF composite spectra (see Figure 1 and the right panel of Figure 2). Our individual $z \sim 1$ sources have colors that are located around both the $z \sim 1$ and $z \sim 2$ tracks indicating a spread in the obscuration of the IRAC colors for these sources. The spread of the individual photometry points in relation to the composite SED is illustrated in Paper I.

The AGN sources (blue symbols) are not completely constrained to the gray shaded region, though our redshift track from the featureless AGN composite SED indicates they should be on average, illustrating a lack of homogeneity in the near- and mid-IR photometry among mid-IR classified AGNs. Most AGNs in our sample do not have a clear stellar bump in the near-IR which restricts them to the shaded region (only 8% (2) of the AGN sources in the gray region have a visible stellar bump). Of the outlying high-redshift AGNs in this plot, the majority (70%) possess a weak visible stellar bump which pushes them into the regions of the color space occupied by SF galaxies. Eleven (50%) of the silicate AGNs, 2 (17%) of the featureless AGNs,
Our sources in IRAC color space with the criteria of Donley et al. (2012) shown as the shaded region. The modified criteria do an effective job of selecting power-law sources while avoiding contamination from SF galaxies but still miss many of our silicate AGNs. (A color version of this figure is available in the online journal.)

The middle panel of Figure 2 is the color space defined by Lacy et al. (2004) where the shaded region is used to identify AGNs. The vast majority of our sources occupy this region, regardless of their power source diagnosed from the mid-IR spectrum (see also Donley et al. 2008, 2012). The SF sources again show a clean redshift separation as the IRAC channels sample the stellar bump. As neither subsample of AGNs similarly exhibits a redshift separation, we do not plot them with different symbols according to redshift. The redshift tracks of the featureless AGN and silicate AGN composite SEDs occupy the same portion of the graph, so we only plot the silicate AGN SED track in orange; the track lies in the upper portion of the graph.

We overplot both SF SED redshift tracks \( z \sim 1 \) in red and \( z \sim 2 \) in purple as they show an interesting separation. At low redshifts \( z < 2 \), the \( z \sim 1 \) SF SED track lies just outside the shaded region, while the \( z \sim 2 \) SF SED lies inside it, but after \( z = 2 \), the tracks lie on top of each other. This difference in the color tracks between our \( z \sim 1 \) and \( z \sim 2 \) composite SEDs is likely due to the different intrinsic \( L_{IR} \) of each subsample. The \( z \sim 1 \) sources are on average LIRGs (\( L_{IR} \sim 4 \times 10^{11} L_\odot \)) and therefore have less dust to obscure the IRAC colors than our \( z \sim 2 \) ULIRG SED composite; adding more dust to a SF galaxy will cause it to shift toward the top-left of this plot, which is exactly the shift we see between our \( z \sim 1 \) and \( z \sim 2 \) SED tracks. At \( z \gtrsim 3 \), the tracks approach the area occupied by the AGN, but as none of our SF sources possess a redshift this high, we are unable to determine if our sources follow our tracks into the upper portion of the graph. Both of the SF SEDs accurately trace the redshift separation exhibited by our sources.

In the right panel of Figure 2, we show on our composite SEDs the effective wavelengths of each of the IRAC bandwidths at redshifts 1, 2, and 3 (blue, green, and red, respectively). These bands straddle the stellar bump over this redshift range. Both AGN SEDs have a power-law shape over these bands causing little evolution in IRAC color space.

The high degree of contamination in these IRAC color–color diagnostics by high-redshift SF galaxies motivated Donley et al. (2012) to create more restrictive criteria than originally presented in Lacy et al. (2004) and Stern et al. (2005). Donley et al. (2012) use a sample of AGNs identified at optical and X-ray wavelengths to construct the new criteria, and now we are able to test these criteria using mid-IR spectroscopic AGNs. We apply the new color cut presented in Donley et al. (2012) to our sample in Figure 3. The authors determined the gray shaded region was the most effective at selecting out AGNs with power-law spectra in the IRAC bandwidths, and indeed, all of our sources that meet the more restrictive criteria have flux densities such that \( S_{3.6} < S_{4.5} < S_{8.0} < S_{15} \). Based on our high-redshift sources, we propose the simple IRAC color cuts of

\[
\log \left( \frac{S_{8.0}}{S_{3.6}} \right) > 0.08
\]

and

\[
\log \left( \frac{S_{8.0}}{S_{4.5}} \right) > 0.15
\]

(solid lines in Figure 3) for selecting potential power-law AGN candidates, similar to the Donley et al. (2012) criteria.

The IRAC color-selection techniques, even using the more restrictive cuts presented in Donley et al. (2012), still miss a large fraction (39% of the present sample) of mid-IR spectroscopically confirmed AGNs, specifically most of the more obscured silicate AGNs. Furthermore, such diagnostics cannot conclusively determine if an AGN is significantly contributing to the bolometric luminosity of a galaxy. Since an IRAC color diagnostic applied at high redshift \( z \gtrsim 1.3 \) is necessarily based on separating sources into AGN or SF dominated based on the shape of the spectrum in the near-IR, such diagnostics might not be the most desirable for determining the dominant power source of dust obscured galaxies in the mid-IR and far-IR regime.

4. NEW COLOR–COLOR DIAGNOSTICS

Our large sample of high-redshift SF and AGN sources, identified with deep mid-IR spectroscopy, and wealth of multiwavelength photometry allows us to define new color–color diagnostics that are well suited to uncovering galaxies harboring an AGN as revealed in the mid-IR spectrum, and galaxies with a bolometrically important AGN. We seek to combine multiple portions of the IR spectrum that are probing the physical nature of each galaxy with different pieces of information. At 3.6 μm, SF galaxies at \( z \sim 1–2 \) will have a stellar bump due to the underlying stellar population, while this effect might be washed out in luminous AGNs, producing a power-law shape. Similarly, at these redshifts, the 24 μm filter will straddle the PAH complexes at 7.7 and 12.7 μm, which will be weakened or absent in a bright AGN. However, there is a caveat that at \( z \sim 1.5 \), the silicate absorption feature present in some AGN spectra, falls into the 24 μm bandwidth which can produce colors that mimic SF galaxies. On the other hand, the bandwidth is large enough that we do not expect this to be a significant source of contamination. The far-IR should have a different shape based on the relative amounts of cold and warm dust emission present, and SF galaxies will have relatively more cold dust than AGNs,
while AGNs have an increased amount of warm dust (Paper I). Finally, the 8 μm filter, at z ∼ 1–2, covers a relatively featureless portion of the spectrum, so when combined with filters that are tracing features, should act as a base to distinguish between AGN and SF systems.

We used available photometry from Herschel and Spitzer ranging from 3.6 to 350 μm (observed) and explored every possible color combination. In addition, we also look at where the composite SEDs lie to get a sense of where we should expect to find AGN and SF galaxies, on average. For color–color plots in which the AGNs were well separated from the SF sources, we calculated the contamination rates of each region. We find that a color diagnostic spanning the full range of the IR spectrum does the best job of separating both AGNs with a pure power-law spectrum from 1 to 10 μm and AGNs with silicate absorption from SF galaxies at high redshift. We define two new color–color diagnostics which, based on having a low contamination and clarity of separation, are the optimal diagnostics to employ when both AGN and SF systems.

4.1. $S_{250}/S_{24}$ versus $S_{8}/S_{3.6}$

We find that combining longer wavelength photometry from Herschel with mid-IR photometry from Spitzer MIPS/IRAC provides the most reliable separation between our mid-IR classified AGN and SF galaxies since they probe the widest range of dust properties affected by AGN and SF activity.

Figure 4 shows $S_{250}/S_{24}$ versus $S_{8}/S_{3.6}$. Both colors cause a separation of sources with the result that the SF-dominated sources lie in the lower right portion of the graph (separated by the diagonal solid line). The SF sources separate weakly according to redshift (indicated by open and filled symbols) with the lower redshift sources lying slightly below the high-redshift sources. The redshift tracks calculated from the $z ∼ 1$ SF SED and $z ∼ 2$ SF SED follow similar evolutionary paths, although again they exhibit a separation in the IRAC color, $S_{8}/S_{3.6}$, with the $z ∼ 2$ SF track redder than the $z ∼ 1$ SF track between $z ∼ 1$ and 2. The SED redshift tracks trace out the area occupied by the SF galaxies according to the redshift separation exhibited by the sources.

The AGNs are loosely separated by the presence or absence of silicate absorption at 9.7 μm in this color–color space. We plot both subsamples according to redshift (filled symbols are $z ∼ 1$ and open symbols are $z ∼ 2$). The featureless AGNs do not contaminate the SF region and lie further to the left. The featureless AGN SED redshift tracks exhibit some slight evolution along the x-axis with redshift, consistent with the individual data points. The featureless AGNs (filled and open squares, according to redshift), on the other hand, show no evolution along the x-axis with redshift but show some spread along the y-axis. The fact that some silicate AGN sources contaminate the SF region can be attributed to two effects, namely that some individual sources possess a weak stellar bump and some sources have more relative cold dust emission in the far-IR. The silicate AGN SED redshift track exhibits no evolution in either direction and so is plotted as a star.

Both color axes produce a separation of AGN and SF sources. Based on the location of our sources, we calculate the separation line to be

$$\log(S_8/S_{3.6}) = 0.74 \times \log(S_{250}/S_{24}) - 0.78$$

(3)

drawn as the bold solid line in Figure 4. In the absence of all four wavelengths, we find that the majority of our AGN sources satisfy either of the following color criteria shown as the dashed lines:

$$\log(S_{250}/S_{24}) < 1.30$$

(4)

$$\log(S_8/S_{3.6}) > 0.32.$$  

(5)

The separation along individual axes is particularly useful if only an upper limit for $S_{250}$ is available when searching for AGNs.
We quantify the contamination of the SF and AGN regions (separated by the diagonal solid line): 10% of the sources (11 of 111 total) in the SF region are AGNs and 2 of the 22 sources (9%) in the AGN region are SF dominated. None of the contaminating AGNs are power law dominated. Some of the individual silicate AGNs have a stellar bump (41%), causing contamination along the $S_8/S_{3.6}$ axis. Furthermore, several of our silicate AGNs (8, or 42%) have significant amount of cold dust emission in the far-IR, producing $S_{250}/S_{24}$ flux density ratios greater than 1.3. The high $S_{250}/S_{24}$ flux ratio correlates with the presence of a stellar bump in the silicate AGN, with 32% possessing both. Finally, it is worthwhile to note that the contaminating AGNs are significantly fainter at 24 $\mu$m (median $S_{24} = 220$ $\mu$Jy) than the AGNs lying in the upper region of the graph (median $S_{24} = 1240$ $\mu$Jy). Indeed, all but one of the properly identified AGNs have $S_{24} > 300$ $\mu$Jy. Based on our sample of 24 $\mu$m bright sources, our diagnostic is optimized to select AGNs with $S_{24} > 300$ $\mu$Jy, though if the physics is similar in lower luminosity AGNs, they will have similar SEDs and colors, in which case our diagnostics can also be used to select out AGN-dominated sources.

$S_{250}$, in comparison with $S_{24}$, is an indicator of the relative amount of cold dust in a galaxy. As an AGN becomes more powerful, the relative amount of warm dust increases, so that the ratio of $S_{250}/S_{24}$ decreases. For galaxies lacking a significant amount of warm dust, the cold dust will be the dominant contributor to the $L_{IR}$. Low $S_{250}/S_{24}$ ratios in our mid-IR AGNs indicate that the warm dust, indicative of an AGN, is significantly contributing to the far-IR emission, and accordingly, the AGN is an important contributor to the bolometric luminosity. Our diagnostic is therefore more powerful than the IRAC diagnostics presented in Section 3 since it selects AGNs significantly contributing to the total IR emission.

Our new diagnostic is a definite improvement over the IRAC selection criteria presented in Lacy et al. (2004) and Stern et al. (2005), though photometry is scarcer. In our sample of 151 galaxies, 99% have IRAC data so both Lacy et al. (2004) and Stern et al. (2005) can be applied, while only 88% have the relevant wavelengths to satisfy our new diagnostic. We verify the more restrictive IRAC criteria of Donley et al. (2012), shown in Figure 3, with our IRS sample, whose mid-IR power source has been determined via spectral decomposition. Our new diagnostic is a slight improvement over the revised IRAC criteria presented in Donley et al. (2012). In the present case, 35% of our AGN sources are misclassified as SF galaxies, while according to the restricted IRAC criteria (Equations (1) and (2)), 39% are misclassified. In addition, with the new criteria, we correctly identify two sources as AGNs that were misclassified using only the IRAC colors. Though the improvements gained in recovering mid-IR AGNs by combining colors covering the entire IR spectrum are only slight over using IRAC colors alone, an added strength of our new criteria lies in the fact that mid-IR data from the WISE can be easily substituted for Spitzer data. The WISE 22 $\mu$m and 3.4 $\mu$m channels correspond to Spitzer 3.6 $\mu$m and 24 $\mu$m bandwidths. We have used the redshift tracks of our templates to determine that the WISE 12 $\mu$m channel is the optimal substitute for Spitzer 8 $\mu$m (see Section 4.4).

The middle panel of Figure 4 illustrates the different SED tracks shown on the left panel. 250 $\mu$m, 24 $\mu$m, 8 $\mu$m, and 3.6 $\mu$m at $z = 1, 2, 3$ are indicated on the composite SEDs. $S_{250}$ traces the far-IR peak of each template while $S_{24}$ traces the mid-IR emission—the different ratios of mid-IR to far-IR emission (or warm to cold dust) in AGN and SF sources produces the observed color separation in $S_{250}/S_{24}$. At the lower wavelengths, $S_8/S_{3.6}$ remains fairly constant for both high-redshift AGN SED templates. As some of our individual AGN sources do show signs of weak SF activity as well as AGN activity, several of our AGNs possess a noticeable stellar bump which causes a spread in $S_8/S_{3.6}$. Of the 11 AGN sources contaminating the SF region, 60% possess a visible stellar bump compared with only 14% of AGN sources in the AGN region. The $z \approx 1$ SF composite SED illustrates how a stellar bump would cause a change in $S_8/S_{3.6}$ with redshift.

In the right panel of Figure 4, we overplot other SED templates in our new color–color space, namely the SEDs of local galaxies and high-redshift submillimeter galaxies (SMGs; Pope et al. 2008). These local SEDs come from combining all known data on these sources including available IRAS (12, 25, 60, 100 $\mu$m), Spitzer (24, 70, 160 $\mu$m), and SCUBA (850 $\mu$m) photometry as well as mid-IR spectroscopy (e.g., Förster Schreiber et al. 2003; Armus et al. 2007). Mrk 231 (red) lies in the AGN region we defined, although contrary to our high-redshift AGN SED templates, it does exhibit some evolution along the $y$-axis. M 82 (blue) does not enter the SF region until $z = 1$ which is most likely due to the fact that it’s SF peaks at a lower IR wavelength than the majority of our high-redshift sources (see Paper I). Both NGC 6240 (orange) and the high-redshift SMG composite (purple) lie in the SF region except at very low redshifts ($z \lesssim 0.5$) and follow the same general redshift evolution as our sources, that is, increasing $S_{250}/S_{24}$ color with increasing redshift. The SMG composite reaches even higher $S_{250}/S_{24}$ colors than our sample which is consistent with their selection at sub-mm wavelengths. The consistency of these other local and high-redshift templates with our new color diagnostics reinforces our confidence in applying this color selection to a wider range of IR luminous, 24 $\mu$m bright galaxies at high redshift.

4.2. $S_{100}/S_{24}$ versus $S_8/S_{3.6}$

In the absence of longer wavelength SPIRE data, we find that we can substitute $S_{100}$ for $S_{250}$ and we still see a nice separation between the SF and AGN galaxies. In the left panel of Figure 5, we use the colors $S_{100}/S_{24}$ and $S_8/S_{3.6}$ to define a region that separates our high-redshift SF- and AGN-dominated galaxies (diagonal solid line). The line of separation is

$$\log(S_8/S_{3.6}) = 0.208 \times \log(S_{100}/S_{24}) + 0.105$$

where mid-IR AGNs lie above the line.

We plot the uncertainties on our redshift tracks as the hashed lined regions. We opt to not to plot these uncertainties in the other plots presented in this work (Figures 2 and 4) for the sake of clarity, and the ranges covered by the uncertainties in this plot are indicative of the spread in the previous figures. As discussed in detail in Paper I, the uncertainties on the composites were calculated by a bootstrapping technique, which indicates how the scatter in the data points affects the calculated median luminosity by resampling with replacement. The uncertainties on our composites are not calculated directly from the intrinsic scatter in the data, but are the standard deviation of the calculated luminosity after resampling the data 10,000 times. Therefore, it is not surprising that uncertainties on the compile tracks do not encompass the full spread of all data points, particularly the silicate AGNs.

The SF region has only a 12% contamination (11 of 92 total galaxies) by AGN sources. The SF-dominated systems
show a clear separation with redshift. We overplot the redshift track of the \( z \sim 1 \) SF composite SED in red, and it traces out the evolution exhibited by our individual sources. There is only one SF source that lies inside the AGN region (causing a contamination rate of 7%), and it not only has a high redshift (\( z = 2.57 \)) but also has a 47% AGN contribution to the mid-IR. The silicate AGNs exhibit no redshift evolution in this color space, but the featureless AGNs display a weak separation. The AGN composite SED tracks (orange and pink) do not move much vertically with redshift since these sources have a simple power-law shape and lack a stellar bump in the rest-frame near-IR.

The middle panel of Figure 5 shows three of our composite SEDs with lines illustrating where the relevant photometry bandwidths lie at a given redshift. The featureless AGNs have a relatively flat spectrum from 20 to 100 \( \mu m \), so the 100 \( \mu m \) flux does not change with redshift whereas the 24 \( \mu m \) flux decreases, causing the evolution along \( S_{100}/S_{24} \). This is not the case for the silicate AGN. The slope from the mid-IR to the far-IR is relatively constant, producing little change in \( S_{100}/S_{24} \) at increasing redshifts.

We have presented a simple IR color–color plot that separates our high-redshift AGN and SF sources. In the right panel of Figure 5, we test our diagnostic by overplotting the redshift tracks of local templates and a high-redshift SMG SED. The local AGN Mrk 231 (red dashed line) lies well outside the SF region while the starburst M 82 (blue) and local ULIRG NGC 6240 (orange) lie inside it for the most part. The SMG redshift track (purple) also lies in the SF region as expected since most SMGs are star formation dominated (e.g., Pope et al. 2008).

Substituting \( S_{160} \) instead of \( S_{100} \) also works well for separating out the AGNs (it has the same contamination rates mentioned above). However, the SF sources do not have a strong redshift separation, although, since \( S_{160} \) is still probing the cold dust at lower redshifts, there is a stronger separation along the \( x \)-axis. The \( S_{100}/S_{24} \) versus \( S_8/S_{5\mu m} \) color space can be used to select SF galaxies based on redshift as well as looking for AGNs.

As an AGN becomes luminous enough to dominate the mid-IR spectrum, it can heat the dust in the host galaxy causing a shift in the SED to warmer average dust temperatures and an increased importance of warm dust to the bolometric luminosity. Based on this, we might expect that just the Herschel PACS and SPIRE colors can be used to preferentially select AGN sources. Hatziminaoglou et al. (2010) searched for a separation using \( S_{350}/S_{250} \) and \( S_{900}/S_{350} \) and found that in the SPIRE bands, their sample of AGNs were indistinguishable from the non-active star-forming galaxies. As many of our sources are not detected or blended at 500 \( \mu m \), we instead combine \( S_{350}/S_{250} \) with \( S_{160}/S_{100} \) and also find that it does not separate the mid-IR classified AGN and SF sources. Figure 1 illustrates that at rest frame wavelengths greater than 40 \( \mu m \), the far-IR portion of the silicate AGN SED and both SF SEDs are all broadly consistent in shape explaining the lack of spread in colors.

4.3. Far-IR Color Selection

As an AGN becomes luminous enough to dominate the mid-IR spectrum, it can heat the dust in the host galaxy causing a shift in the SED to warmer average dust temperatures and an increased importance of warm dust to the bolometric luminosity. Based on this, we might expect that just the Herschel PACS and SPIRE colors can be used to preferentially select AGN sources. Hatziminaoglou et al. (2010) searched for a separation using \( S_{350}/S_{250} \) and \( S_{900}/S_{350} \) and found that in the SPIRE bands, their sample of AGNs were indistinguishable from the non-active star-forming galaxies. As many of our sources are not detected or blended at 500 \( \mu m \), we instead combine \( S_{350}/S_{250} \) with \( S_{160}/S_{100} \) and also find that it does not separate the mid-IR classified AGN and SF sources. Figure 1 illustrates that at rest frame wavelengths greater than 40 \( \mu m \), the far-IR portion of the silicate AGN SED and both SF SEDs are all broadly consistent in shape explaining the lack of spread in colors.

The less pronounced differences in far-IR portions of the composite SEDs is also reflected by the failure of \( S_{250} \) thresholds alone to preferentially select AGNs from the larger GOODS survey of galaxies (discussed below; see Table 3 and Section 5). Our AGN sources, particularly the featureless AGNs, are significantly brighter than our SF sources at 24 \( \mu m \) and 8 \( \mu m \). Therefore, it is not surprising that we found the largest separation between the AGN and SF sources when combining mid-IR with far-IR photometry. We caution that with only far-IR information it is difficult to determine the impact of the AGN on the full IR SED. The most reliable selection of AGN candidates come from combining data from 3.6 \( \mu m \) to 250 \( \mu m \) (Sections 4.1
We do not have WISE photometry for our sources, but we can use the WISE transmission filters to create synthetic photometry using the IRS spectra and the appropriate transmission filters at 12 and 22 μm. For the 3.4 and 4.6 μm filters, we substitute the appropriate IRAC photometry. We have applied a small correction to the IRAC photometry (0.94 for the 3.6 μm filter and 1.04 for the 4.5 μm filter), which we have calculated by comparing the responses of our composite SEDs to each of the WISE and IRAC transmission filters. In addition, we calculate the redshift tracks of our composite SEDs by convolving with the appropriate WISE filters, and we plot our synthetic photometry and redshift tracks in Figure 6.

Colors combining the first three channels, 3.4, 4.6, and 12 μm, are capable of selecting hyperluminous (L_{IR} > 10^{13} L_{⊙}) galaxies, particularly AGNs/QSOs (Bridge et al. 2012; Eisenhardt et al. 2012; Stern et al. 2012; Yan et al. 2012). Stern et al. (2012) found that the WISE color cut [3.4] − [4.6] > 0.8 separates luminous AGNs, which have been classified as such based on meeting the criteria in Stern et al. (2005; see Figure 2). As a complement to these techniques, we would like to separate luminous SF galaxies at high redshift. We find that only combining the first three WISE channels does not effectively separate our SF sources. The strongest separation of our tracks is produced by combining all four WISE channels as shown in Figure 6. We overplot the AGN criterion of Stern et al. (2012) for AGNs with [3.4] − [4.6] > 0.8 as the gray dashed line. Our AGN redshift track confirms the Stern et al. (2012) criterion for AGNs with z ∼ 0.5–1.0 and z ∼ 3. However, none of our sources has a power-law slope steep enough in the appropriate wavelength range to meet this criterion.

Figure 6 illustrates that the strongest separation of our sources and redshift tracks is for SF galaxies at z ∼ 2 due to prominent PAH features lying in the 22 μm transmission filter. The sensitivity depths at 12 and 22 μm are ∼1 and ∼6 mJy, respectively (Wright et al. 2010). Given the sensitivity limits, at a redshift of ∼2, a SF galaxy would need to be at least an ULIRG and probably even a hyper-ULIRG (L_{IR} > 10^{12} L_{⊙}) to be detected by WISE. A benefit of this color-selection technique is that few, if any, extragalactic sources with luminosities less than the ULIRG threshold should occupy the same region as the z ∼ 2 ULIRGs. Therefore, our WISE color-selection method is useful for selecting the brightest SF galaxies at z ∼ 2. In the absence of WISE photometry, Spitzer photometry can be used in similar combinations, with either 8 μm or 16 μm substituting for S_{12} (e.g., Ivison et al. 2004; Pope et al. 2008).

4.4. Mid-IR Color Selection

There is now an abundance of mid-IR photometry as a result of two prominent mid-IR space telescopes: Spitzer and WISE. Past studies have used Spitzer color combinations to separate out mid-IR selected AGN and SF systems (e.g., Ivison et al. 2004; Pope et al. 2008), and emerging studies show that WISE colors can effectively separate IR luminous AGNs (Bridge et al. 2012; Eisenhardt et al. 2012; Stern et al. 2012; Yan et al. 2012). We are motivated by these studies to investigate how well the WISE photometry can separate our high-redshift sources, particularly the SF galaxies. WISE has four transmission filters centered at 3.4, 4.6, 12, and 22 μm, and though WISE photometry is less sensitive than Spitzer data, it has the advantage that it is an all-sky survey and can be used to search for high-redshift objects in regions of the sky not previously well studied.

![Figure 6](image_url)
Table 4
Percentage of AGN and SF Field Galaxies According to \( S_{100}, S_{24}, \) and \( S_{8} \) Strength

| Range (mJy) | \% AGN (No.) | \% SF (No.) | Range (\( \mu Jy \)) | \% AGN (No.) | \% SF (No.) | Range (\( \mu Jy \)) | \% AGN (No.) | \% SF (No.) |
|-------------|--------------|-------------|----------------------|--------------|-------------|----------------------|--------------|-------------|
| <5          | 5 (40)       | 95 (779)    | <200 \( S_{24} \)  | 3 (22)       | 97 (613)    | <40 \( S_{8} \)  | 3 (21)       | 97 (741)    |
| 5–15        | 15 (29)      | 85 (165)    | 200–600 \( S_{24} \) | 9 (35)       | 91 (337)    | 40–200 \( S_{8} \) | 13 (33)      | 87 (222)    |
| >15         | 36 (25)      | 64 (44)     | >600 \( S_{24} \)  | 49 (37)      | 51 (38)    | >200 \( S_{8} \)  | 62 (40)      | 38 (25)     |

Notes. Data correspond to the bottom panels of Figure 7 which shows GOODS-N and GOODS-S field galaxies plotted on our color diagnostic presented in Figure 5. AGN sources (94 total) are those lying above the solid line indicated on the plot. In this table, we calculate the percentage (number) of AGN and SF sources in a given flux density range for \( S_{100}, S_{24}, \) and \( S_{8} \).

Figure 7. Our new color diagnostic for separating AGN and SF galaxies presented in Figures 4 and 5 (top and bottom panels, respectively) applied to our full sample of MIPS 24 \( \mu m \) selected galaxies in the GOODS fields which have corresponding Herschel photometry taken in the GOODS-Herschel survey. In the left panels, we color code galaxies according to their 250 \( \mu m \) flux density (or 100 \( \mu m \) flux density); in the middle panels, according to 24 \( \mu m \) flux density; and in the right panels, according to 8 \( \mu m \) flux density. The region below the solid lines are the same as we defined in Figures 4 and 5; a source lying above the line we label as AGN dominated in the mid-IR (based on our extensive mid-IR spectroscopic sample). Our new diagnostics indicate that roughly \( \sim 8\% \) of the GOODS-Herschel galaxies have an AGN dominating the mid-IR luminosity. Breaking things down as a function of flux density, we find that sources with the brightest \( S_{24} \) and \( S_{8} \) are predominantly AGNs, whereas \( S_{250} \) and \( S_{100} \) do not preferentially select AGNs at brighter flux densities (see Tables 3 and 4). (A color version of this figure is available in the online journal.)

AGNs missed by X-ray surveys. We use Chandra surveys of the GOODS fields (Alexander et al. 2003; Luo et al. 2008) to determine if our diagnostics select galaxies that are obscured and lack an X-ray detection. For \( S_{250}/S_{24} \) versus \( S_{8}/S_{3.6} \), the X-ray detection fraction is 75% for AGNs lying above the solid line and drops to 36% for AGNs lying in the region dominated by SF galaxies. For \( S_{100}/S_{24} \) versus \( S_{8}/S_{3.6} \), the X-ray detection fraction for AGNs above the solid line is 79%, comparable to
the detection fraction for the $S_{250}/S_{24}$ versus $S_8/S_{1.6}$ diagnostic. However, in the SF region, the X-ray detection fraction of AGN sources is 60%. Approximately 40% of the X-ray undetected AGNs lie above the solid lines in both diagnostics, making our color-selection criteria useful for selecting galaxies dominated by an AGN in the IR regardless of the level of obscuration. It is interesting to note that ~60% of our mid-IR dominated AGNs would not be classified as such based on either X-ray data or the $S_{250}/S_{24}$ and $S_8/S_{1.6}$ colors. The AGNs embedded in these galaxies are not having a strong enough effect on the far-IR and near-IR portions of the spectrum to distinguish them from SF galaxies on the basis of colors, although the AGNs are having an effect on the mid-IR emission. This could be a product of viewing angle, or possibly even an evolutionary sequence where as the AGN grows more luminous, it will be reflected in its IR colors (see Paper I for a full discussion).

5. APPLICATION OF NEW COLOR–COLOR DIAGNOSTIC TO ALL GOODS-HERSHEY GALAXIES

We now apply our new diagnostics defined above to broadly separate SF- and AGN-dominated galaxies in the whole GOODS-Herschel survey (Elbaz et al. 2011). We plot all galaxies in GOODS-N and GOODS-S detected in all four bands on our two new color–color plots in Figure 7. We use the color cuts derived in Sections 4.1 and 4.2 (Equations (3) and (6)) to separate sources dominated by AGN and SF activity in the mid-IR. Using the $S_{250}/S_{24}$ versus $S_8/S_{1.6}$ plot (top panels), we have a total of 665 galaxies with detections in all four bandwidths in GOODS-N and GOODS-S, of which 58 (9%) lie in the AGN region. For $S_{100}/S_{24}$ versus $S_8/S_{1.6}$ (bottom panels), we have 988 sources with detections in all four bandwidths, of which 94 (10%) lie in the AGN region. Both diagnostic plots lead to a similar fraction of GOODS-Herschel sources being AGN dominated in the mid-IR.

It has been found that bright 24 $\mu$m flux density correlates with mid-IR AGN indicators at high redshift and in local ULIRGs (Desai et al. 2007; Dey et al. 2008; Donley et al. 2008, respectively). Given this trend, we look to quantify the fraction of galaxies that are AGN dominated in the mid-IR as a function of flux density using our new color–color plots. In Figure 7, we plot all GOODS-Herschel galaxies with different colored symbols depending on their flux density (see legend for each panel). Our diagnostic was determined using 24 $\mu$Jy bright sources, and applied to our own sample, the diagnostic primarily recovered AGN with $S_{24}>300$ $\mu$Jy. Furthermore, the contribution of the AGN to the mid-IR has been shown to increase with increasing 24 $\mu$m flux density, particularly at higher redshift ($z>0.6$ Brand et al. 2006). Therefore, it is perhaps not surprising that only one fainter source ($S_{24}<200$ $\mu$Jy) is found in the AGN region in Figure 7. It is clear that a larger fraction of sources are in the AGN region of the color–color plot for the brightest 24 $\mu$m and 8 $\mu$m flux densities, whereas the 250 $\mu$m and 100 $\mu$m flux densities do not make as much of a difference to the AGN fraction. We quantify the fraction of sources in each flux bin that are classified as AGN and SF dominated based on these color–color plots in Tables 3 and 4. Our results show that the presence of an AGN is only visible as an excess in the mid-IR, while the far-IR photometry alone is largely insensitive to the physics of the nuclear power source. We therefore conclude that the flux limit of a mid-IR survey has a big effect on the fraction of sources which have a significant AGN whereas far-IR/sub-mm fluxes correlate less strongly with AGN fraction.

Figure 8. The percentage of AGN and SF sources (with Poisson error bars) greater than a given 24 $\mu$m flux density. Sources are taken from the GOODS fields and defined as an SF or AGN galaxy based on their position in $S_{250}/S_{24}$ vs. $S_{8}/S_{1.6}$ color space (see top panels of Figure 7). The brightest flux densities are dominated by AGNs, illustrating that applying a flux density cut in $S_{24}$ is useful for selecting a population with a large percentage of AGNs.

Using the data in Table 3, we plot the percentage of galaxies which are classified as AGN and SF greater than a given 24 $\mu$m flux density in Figure 8. The fraction of AGN sources shows a steady increase with 24 $\mu$m flux density. Above $S_{24} \sim 750$ $\mu$Jy, the majority of galaxies selected at these wavelengths will be AGN dominated. In Table 1, we compare the intrinsic luminosities of our composite SEDs. Despite our AGN SEDs having an $L_{IR}$ below that of the $z \sim 2$ SF SED, the AGN subsamples have a higher median $S_{24}$ flux density, particularly the featureless AGN. This effect is due to the differing ratios of far-IR to mid-IR luminosity. With the possible exception of $z \sim 2$, where the brightest PAH complex falls in the 24 $\mu$m filter, at all redshifts AGNs should comprise the majority of galaxies above $S_{24} > 750$ $\mu$Jy despite possibly being less intrinsically luminous in the IR than SF galaxies (see Paper I for a direct comparison of our SEDs).

6. CONCLUSIONS

We have combined deep photometry from 3.6 to 500 $\mu$m with Spitzer mid-IR spectroscopy for 151 high-redshift ($z>0.5$) (U)LIRGs in order to explore the relative positions of high-redshift mid-IR AGN and SF galaxies in IR color space. We start by applying color–color diagnostics based on IRAC colors alone (Lacy et al. 2004; Stern et al. 2005) to our high-redshift sample and find that there is significant contamination of SF sources in the AGN regions; however, our mid-IR spectroscopic sample confirms the new IRAC color diagnostics from Donley et al. (2012). Adding 24 $\mu$m photometry does not effectively separate all of the AGN, but it does produce a separation of the SF galaxies according to redshift. The same separation of SF galaxies is produced by plotting our redshifted SED tracks in color–color graph using the WISE transmission filters.

Our high-redshift AGN and SF sources exhibit different spectral features and SED shape in the near-, mid-, and far-IR/sub-mm wavelengths. We explore combining photometry from all three IR ranges for an optimal selection technique. In addition to photometry, we explore where AGN or SF sources should lie on average in different color combinations by using redshift tracks of our composite SEDs. We present two new color–color diagnostics combining Spitzer mid-IR and Herschel far-IR photometry that can be used to estimate whether a galaxy harbors an AGN in the absence of IRS spectroscopy. The optimal color diagnostics for bright $S_{24}$ sources spanning
the full IR spectrum are $S_{250}/S_{24}$ versus $S_{8}/S_{3.6}$ and $S_{100}/S_{24}$ versus $S_{8}/S_{3.6}$. These diagnostics have a low contamination rate of $\sim 10\%$ in each of the SF- and AGN-occupied regions, and the contaminating AGNs chiefly have $S_{24} < 300 \mu$Jy. Moreover, the $S_{250}/S_{24}$ color estimates if an AGN is significantly contributing to the bolometric output of a galaxy. The mid-IR photometry from WISE can also be used in conjunction with Herschel photometry to separate out AGNs. When only limited data are available, either of the colors $S_{250}/S_{24}$ or $S_{8}/S_{3.6}$ can be used alone to select AGNs.

We apply our new color–color diagnostics to the entire GOODS-Herschel survey to determine the fraction of sources which are dominated by AGN and SF activity. We find roughly 10% of GOODS-Herschel galaxies have a significant AGN. We also confirm that a higher fraction ($\gtrsim 50\%$) of the brightest sources, $S_{8} > 200 \mu$Jy or $S_{24} > 600 \mu$Jy, have colors indicative of a bolometrically significant AGN. The 100 $\mu$m and 250 $\mu$m fluxes show a much weaker dependence on AGN fraction, though when combined with $S_{24}$, $S_{250}$ effectively separates out the AGN, indicating that the amount of cold dust emission relative to mid-IR emission is a good indicator of the IR power source. We conclude then that far-IR fluxes or colors alone cannot be used to determine the nature of the IR power source, and the most effective method is to combine mid-IR and far-IR data.

We thank the anonymous referee for the careful reading of this paper and the insightful comments provided. This work is based in part on observations made with Herschel Space Observatory, a European Space Agency Cornerstone Mission with significant participation by NASA, and the Spitzer Space Telescope, which is operated by the Jet Propulsion Laboratory, California Institute of Technology under a contract with NASA. Support for this work was provided by NASA through an award issued by JPL/Caltech.

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