ORIGIN OF 12 μm EMISSION ACROSS GALAXY POPULATIONS FROM WISE AND SDSS SURVEYS

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ABSTRACT

We cross-matched Wide-field Infrared Survey Explorer sources brighter than 1 mJy at 12 μm with the Sloan Digital Sky Survey galaxy spectroscopic catalog to produce a sample of ∼108 galaxies at (z) = 0.08, the largest of its kind. This sample is dominated (70%) by star-forming (SF) galaxies from the blue sequence, with total IR luminosities in the range ∼10^8–10^12 L☉. We identify which stellar populations are responsible for most of the 12 μm emission. We find that most (~80%) of the 12 μm emission in SF galaxies is produced by stellar populations younger than 0.6 Gyr. In contrast, the 12 μm emission in weak active galactic nuclei (AGNs; L_{[OIII]} < 10^9 L☉) is produced by older stars, with ages of ~1–3 Gyr. We find that L_{12 μm} linearly correlates with stellar mass for SF galaxies. At fixed 12 μm luminosity, weak AGNs deviate toward higher masses since they tend to be hosted by massive, early-type galaxies with older stellar populations. SF galaxies and weak AGNs follow different L_{12 μm}–SFR (star formation rate) relations, with weak AGNs showing excess 12 μm emission at low SFR (0.02–1 M⊙ yr⁻¹). This is likely due to dust grains heated by older stars. While the specific star formation rate (SSFR) of SF galaxies is nearly constant, the SSFR of weak AGNs decreases by ~3 orders of magnitude, reflecting the very different star formation efficiencies between SF galaxies and massive, early-type galaxies. Stronger type II AGNs in our sample (L_{[OIII]} > 10^9 L☉), act as an extension of massive SF galaxies, connecting the SF and weak AGN sequences. This suggests a picture where galaxies form stars normally until an AGN (possibly after a starburst episode) starts to gradually quench the SF activity. We also find that 4.6–12 μm color is a useful first-order indicator of SF activity in a galaxy when no other data are available.

Key words: infrared: galaxies – galaxies: active – surveys

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1. INTRODUCTION

A detailed picture of the present-day galaxy populations, their evolution and emission properties across different wavelengths, is still far from complete. Surveys like the Sloan Digital Sky Survey (SDSS; York et al. 2000) have collected large amounts of information in the optical regime, while Two Micron All Sky Survey (Skrutskie et al. 2006) and the IRAS mission (Neugebauer et al. 1984) have provided valuable, albeit relatively shallow, data sets from J band up to 100 μm. More recently, the Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010) has completed mapping the whole sky in the mid- and far-infrared, at sensitivities much deeper than any other large-scale infrared survey. For example, WISE is about 100 times more sensitive at 12 μm than IRAS.

While our understanding of the optical and far infrared (FIR) properties of galaxies (longward of 24 μm) has grown steadily, thanks mainly to Spitzer and Herschel, the spectral region between 10 and 15 μm remains comparatively unexplored. In normal galaxies, the light at the redder optical bands and in the J, H, and K near-IR bands is closely tied to the total mass of the galaxy, as it is dominated by the red population of older stars. At wavelengths longer than ~8 μm, emission from dust heated by younger stars becomes increasingly relevant and begins to trace the star formation rate (SFR).

The rate at which galaxies transform gas into stars is one of the most fundamental diagnostics that describes the evolution of galaxies. Of major importance is to find what physical parameter(s) drive changes in the SFR. As dust-reprocessed light from young stars is re-emitted mainly in the FIR regime, the FIR luminosity is one of the best tracers of star formation activity (Kennicutt 1998). It is well known that commonly used SFR indicators, such as the UV continuum and nebular emission line fluxes, require sometimes substantial corrections for dust extinction. Furthermore, these corrections are highly uncertain and difficult to derive. For this reason, integrated estimators based on the total infrared (IR) luminosity, either alone or in combination with the ultraviolet luminosity (e.g., Heckman et al. 1998), and monochromatic estimators based mainly on 24 μm fluxes, alone or in combination with Hα luminosity (e.g., Wu et al. 2005; Alonso-Herrero et al. 2006; Calzetti et al. 2007; Zhu et al. 2008; Rieke et al. 2009; Kennicutt et al. 2009), are increasingly being considered as reliable star formation indicators for normal and dusty star-forming (SF) galaxies. The use of any IR flux as an SFR indicator relies on the assumption that the IR continuum emission is due to warm dust grains heated by young stars. However, there is also a contribution to dust reprocessed emission by old stellar populations, associated more with the interstellar medium around evolved stars than with recently born stars. In addition, some fraction of the IR luminosity may be attributed to active galactic nuclei (AGNs), if present (in Section 3.8 we find AGN emission is of minor importance).
importance in most of our sample). The exact contribution of each component is difficult to estimate without detailed spectral analysis.

Chary & Elbaz (2001) and Rieke et al. (2009) found correlations between the 12 μm luminosity and the total IR luminosity for small samples of nearby galaxies. Duc et al. (2002) found that sources in A1689 with high Infrared Space Observatory (ISO) mid-IR color index [15 μm]/[6.75 μm] are mostly blue, actively SF galaxies, while low mid-IR flux ratios correspond to passive early-type systems. They suggest that 15 μm emission is a reliable indicator of obscured star formation. Similarly, shorter wavelength mid-IR emission such as WISE 12 μm is expected to be a practical tracer of star formation activity.

An important caveat is that far-infrared and/or radio measurements are only available for a small fraction of known galaxies. Early work by Spinoglio & Malkan (1989) using IRAS all-sky data used 12 μm to select unbiased samples of active galaxies with fluxes above 220 mJy and to study their luminosity function. Deep pencil beam surveys have complemented these samples with high-redshift data. Seymour et al. (2007) conducted a 12 μm survey of the ESO-Scuolter field (700 arcmin²) with the ISO satellite down to 0.24 mJy. Rocca-Volmerange et al. (2007) used it to model mid-IR galaxy counts, revealing a population of dusty, massive ellipticals in ultraluminous infrared galaxies (ULIRGs). Teplitz et al. (2011) performed imaging of the GOODS fields (150 arcmin²) at 16 μm with the Spitzer spectrometer, finding that ~15% of objects are potentially AGNs at their depth of 40–65 μJy. These surveys illustrate the necessary tradeoff between depth and area covered, potentially limiting the statistical significance of results due to cosmic variance. WISE provides the data to significantly improve the situation. Our sample of ~10³ galaxies (see below) is over 200 times more sensitive than IRAS-based surveys and covers an area ~370 times larger than the GOODS samples.

In this work we explore the physical properties of 12 μm selected galaxies in the local universe, using a large sample of SF galaxies and AGNs with available redshifts and emission line measurements from the SDSS. This is by far the largest 12 μm sample to date, and we use it to trace the origin of IR emission across different galaxy populations and to investigate how IR emission relates to stellar mass. We also explore using 12 μm luminosity as a proxy for SFR to distinguish intense starburst activity from quiescent star formation. Since we employ the SDSS spectroscopic catalog, our results apply to relatively bright galaxies at low redshift. WISE certainly recovers other populations of galaxies, ranging from low metallicity blue compact dwarf galaxies at very low redshift (Griffith et al. 2011) to highly obscured sources at high redshift (Eisenhardt et al. 2012). Lake et al. (2012) shows that WISE detects L’ galaxies out to z ~ 0.8 in the 3.4 μm band, while Stern et al. (2012) shows that WISE is a very capable AGN finder, sensitive to both obscured and unobscured QSOs. A companion paper by L. Yan et al. (2011, in preparation) analyzes more diverse galaxy populations observed by WISE and SDSS (including deeper photometric SDSS objects), while here we focus on 12 μm selected sources with available spectra.

This paper is organized as follows. In Section 2, we describe the surveys used in this work as well as explain the construction of our joint WISE–SDSS sample. In Section 3, we characterize the galaxy populations and present the results on the analysis of the mid-IR emission and SFR. Finally, Section 4 summarizes our results and discusses the implications of this work.

Throughout the paper we assume a flat ΛCDM cosmology, with Ωm = 0.3 and ΩΛ = 0.7. We adopt H0 = 70 km s⁻¹ Mpc⁻¹.

2. DATA

2.1. The Wide-field Infrared Survey Explorer Catalog

WISE has mapped the full sky in four bands centered at 3.4, 4.6, 12, and 22 μm, achieving 5σ point-source sensitivities better than 0.08, 0.11, 1, and 6 mJy, respectively. Every part of the sky has been observed typically around 10 times, except near the ecliptic poles where the coverage is much higher. Astrometric precision is better than 0.15″ for high signal-to-noise (S/N) sources (Jarrett et al. 2011) and the angular resolution is 6′.1, 6′.4, 6′.5, and 12′ for bands ranging from 3 μm to 22 μm.

This paper is based on data from the WISE Preliminary Release 1 (2011 April), which comprises an image atlas and a catalog of over 257 million sources from 57% of the sky. An object is included in this catalog if: (1) it is detected with S/N ≥ 7 in at least one of the four bands, (2) is detected on at least five independent single-exposure images in at least one band, (3) has S/N ≥ 3 in at least 40% of its single-exposure images in one or more bands, and (4) is not flagged as a spurious artifact in at least one band. We refer the reader to the WISE Preliminary Release Explanatory Supplement for further details7 (Cutri et al. 2011).

2.2. The MPA–JHU Sloan Digital Sky Survey Catalog

The SDSS (York et al. 2000; Stoughton et al. 2002) is a five-band photometric (ugriz) bands and spectroscopic survey that has mapped a quarter of the sky, providing photometry, spectra, and redshifts for about a million galaxies and quasars. The MPA–JHU catalog (Brinchmann et al. 2004, hereafter B04) is a value-added catalog based on data from the Seventh Data Release (DR7; Abazajian et al. 2009) of the SDSS.8 It consists of almost 10⁶ galaxies with spectra reprocessed by the MPA–JHU team, for which physical properties based on detailed emission line analysis are readily available. Here, we give a brief description of the catalog and the methodology employed to estimate SFRs. We refer the reader to the original papers for an in-depth discussion.

The MPA–JHU catalog classifies galaxies according to their emission lines, given the position they occupy in the BPT (Baldwin et al. 1981) diagram that plots the [O iii] λ5007/Hβ versus [N ii] λ6584/Hα flux ratios. This separates galaxies with different ionizing sources as they populate separate sequences on the BPT diagram. In most galaxies, normal star formation can account for the flux ratios. However, in some cases an extra source such as an AGN is required. In this paper, we follow this BPT classification to distinguish between: (1) SF galaxies (class SF and low S/N SF from B04), (2) AGNs (class AGN and low S/N LINER from B04), and (3) composite systems that present signatures of the two previous types (class C from B04). Note that broad-lined AGN-like quasars and Seyfert 1 galaxies are not included in the sample, as they were targeted by different criteria by the SDSS.

SFRs are derived by different prescriptions depending on the galaxy type. The methodology adopted by B04 is

7 WISE data products and documentation are available at http://irsa.ipac.caltech.edu/Missions/wise.html
8 The MPA–JHU catalog is publicly available at http://www.mpa-garching.mpg.de/SDSS/DR7/
based on modeling emission lines using Bruzual & Charlot (1993) models along with the CLOUDY photoionization model (Ferland 1996) and spectral evolution models from S. Charlot & G. Bruzual (2008, in preparation) to subtract the stellar continuum. To correct lines for dust attenuation, MPA–JHU adopts the multicomponent dust model of Charlot & Fall (2000), where discrete dust clouds are assumed to have a finite lifetime and a realistic spatial distribution. This approach produces SFRs that take full advantage of all modeled emission lines. For AGNs and composite galaxies in the sample, SFRs were estimated by the relationship between the $D_{4000}$ spectral index and the specific SFR (SFR/$M_{\odot}$ or SSFR), as calibrated for SF galaxies (see Figure 11 in B04). These estimates have been corrected in the latest MPA–JHU DR7 release by using improved dust attenuations and improved aperture corrections for non-SF galaxies following the work by Salim et al. (2007). Gas-phase oxygen abundances, $12 + \log(O/H)$, are available for SF galaxies as calculated by Tremonti et al. (2004). Throughout this paper we adopt the spectral line measurements as well as estimates of SFR, metallicity, and dust extinction given by the MPA–JHU catalog.

The SDSS pipeline calculates several kinds of magnitudes. In this work we have adopted modified Petrosian magnitudes for flux measurements, which capture a constant fraction of the total light independent of position and distance. When appropriate, we have also used model magnitudes (modelMag) as they provide the most reliable estimates of galaxy colors. Magnitudes are corrected for galactic reddening using the dust maps of Schlegel et al. (1998).

2.3. The Joint WISE–SDSS Galaxy Sample

We have cross-matched data from WISE and the MPA–JHU catalog to construct a galaxy sample covering an effective area of 2344 deg$^2$, or 29% of the DR7 (legacy) spectroscopic footprint. WISE sources were selected to have 12 μm fluxes above 1 mJy, also requiring objects to have clean photometry at 3.4, 4.6, and 12 μm. For MPA–JHU sources, we selected objects with de-reddened Petrosian magnitude $r_{\text{petro}} < 17.7$ and $r$-band surface brightness $\mu_r < 23$ mag arcsec$^{-2}$. This selects a conservative version of the SDSS main galaxy sample (see Strauss et al. 2002). Using a matching radius of 3" we find 96,217 WISE objects with single optical matches (40% of the SDSS sample in the intersection area) and 73 sources with two or more counterparts. The latter are mostly large extended sources or close interacting systems of two members. For the rest of this paper we will focus on the single IR–optical matches that constitute the vast majority (99.9%) of the galaxy population. By using random catalogs generated over the effective area, the expected false detection fraction at 3" is 0.05%.

Each region of the sky has been observed at least 10 times by WISE, with the number of observations increasing substantially toward the ecliptic poles. Within our effective area, the median coverage depth at 12 μm is about 13, varying typically between 10 and 20. At these levels, the average completeness of the sample is expected to be over 90%, as shown in the WISE Preliminary Release Explanatory Supplement (Section 6.6).

3. ANALYSIS AND RESULTS

3.1. Derived Properties

We derived stellar masses for all galaxies using the $k$correct algorithm (Blanton & Roweis 2007), which fits a linear combination of spectral templates to the flux measurements for each galaxy. These templates are based on a set of Bruzual & Charlot (2003) models that span a wide range of star formation histories, metallicities, and dust extinction. This algorithm yields stellar masses that differ by less than 0.1 dex on average from estimates using other methods (for example, the method based on fitting the 4000 Å break strength and H$\delta$ absorption index proposed by Kauffmann et al. 2003b).

To derive rest-frame colors and monochromatic luminosities in the infrared we used the fitting code and templates of Assef et al. (2010), applied to our combined $ugriz$ photometry plus WISE 3.4 μm, 4.6 μm, and 12 μm fluxes. Assef et al. (2010) present a set of low-resolution empirical spectral energy distribution (SED) templates for galaxies and AGNs spanning the wavelength range from 0.03 μm to 30 μm, constructed with data from the NOAO Deep Wide-field Survey Boötes field (Jannuzi et al. 2010) and the AGN and Galaxy Evolution Survey (C. Kochanek et al. 2011, in preparation). The code fits three galaxy SED templates that represent an old stellar population (elliptical), a continuously SF population (spiral), and a starburst component (irregular), plus an AGN SED template with variable reddening and intergalactic medium absorption. These templates have been successfully used to test the reliability of IRAC AGN selection and to predict the color–color distribution of WISE sources (Assef et al. 2010). We also use these templates to assess the relative contribution of AGNs to the energy budget.

Instead of trying to derive a new calibration of the SFR in the IR, we take the approach of comparing IR luminosities directly to optical dust-corrected SFRs. This makes our results largely independent of any particular SFR calibration. Note all optical SFRs used in this paper have been corrected for dust extinction.

3.2. General Properties of 12 μm Galaxies

We begin our analysis by exploring the general properties of the WISE 12 μm selected galaxy sample. The sample is composed of a mixture of 70% SF galaxies, 12% composite galaxies, and 3% galaxies lacking BPT classification due to the absence of detectable lines in the spectra (most lack Hα emission). The composition of the MPA–JHU optical sample is 44% SF, 12% AGNs, 6% composite, and 37% unclassifiable, which means that the 12 μm selection is highly efficient in recovering SF systems and avoids objects with weak or no emission lines. In terms of the total optical galaxy populations, 61% (SF), 53% (AGNs), and 76% (composite) of the SDSS galaxies have 12 μm flux densities above 1 mJy. In Figure 1 (top row) we plot the distribution of redshift, stellar mass, $D_{4000}$ index, and rest-frame $u$$-$$r$ color for SF galaxies, AGNs, and composite systems, as well as for the three classes all together. The majority of WISE–SDSS 12 μm sources are SF galaxies at $z = 0.08$ with stellar masses of $\sim 10^{10.3} M_{\odot}$; these are typical values for the SF class. They clearly populate the blue peak of the galaxy bimodal distribution around $(u - r)_0 = 1.6$ and have inherently young stellar populations ($D_{4000} \sim 1.3$, or ages of $\sim 0.5$ Gyr). AGNs are, as expected, comparatively more massive ($M^* \sim 10^{10.7} M_{\odot}$), redder $(u - r)_0 = 2.1$, and older $(\sim 1–6$ Gyr), dominating the massive end of the 12 μm galaxy distribution. As a population, AGNs do not differ significantly (in terms of these properties) in comparison to the corresponding purely optical sample. Composite galaxies present intermediate properties between the SF and AGN samples. Note that the

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9 Templates and code are available at http://www.astronomy.ohio-state.edu/~rjassef/lrt/
bulk of galaxies lacking BPT classification (due to weak or absent emission lines) is missed in our IR–optical sample. These objects primarily populate the red sequence of the galaxy distribution (e.g., Baldry et al. 2004), and hence are not expected to be prominent at 12 μm.

We then divide the sample into three subsamples of monochromatic infrared luminosity: faint \((L_{12}\mu m < 10^{9.2} L_\odot)\), intermediate \((10^{9.2} L_\odot < L_{12}\mu m < 10^{10} L_\odot)\), and bright \((L_{12}\mu m > 10^{10} L_\odot)\) sources. There are no large biases with redshift, i.e., the different classes are sampled roughly without preference at all luminosities. Both SF galaxies and AGNs become more massive for higher IR luminosities and we have checked that this also holds in narrow redshift slices. As we will show below, this is due to the coupling between the IR and the optical emission. Interestingly, the 12 μm SF galaxies change by a factor of 0.8 dex in mass toward high 12 μm luminosities while keeping the same color and stellar content. The AGN population, while getting slightly more massive, becomes bluer and dominated by younger stars as IR luminosity increases.

Figure 2 shows the redshift distribution of the rest-frame 12 μm luminosity for our sample. It can be seen that while high luminosity sources naturally lie at higher redshifts, the redshift distribution of the different classes is very similar, except at the lowest redshifts \((z < 0.02)\) where very few AGNs/composite galaxies are observed.

The absence of red-sequence galaxies in our sample is not surprising, but there is also a number of SF galaxies without IR emission due to our flux limit. Figure 3 shows the mass, redshift, and colors of SF galaxies with and without 12 μm emission, as well as for the entire SF optical sample. On average, SF galaxies not present in our sample have bluer colors, lie at lower redshifts, and have stellar masses around \(10^{9.3} M_\odot\), roughly an order of magnitude below the 12 μm SF galaxy sample. At this level, galaxies have very little dust mass, and hence cannot re-radiate much in the IR.

The main result here is that WISE 12 μm selected galaxies are primarily typical blue-sequence (SF) galaxies. It is safe to assume that the majority of blue-sequence galaxies correspond to late morphological types (e.g., Strateva et al. 2001; Shimasaku et al. 2001; Baldry et al. 2004). AGNs and composite objects are also represented, belonging either to the red sequence or to a transitional regime among the two former classes. It is interesting that the detection efficiency is largest for composite systems, which was also found by Salim et al. (2009) for 24 μm sources that lie in the so-called green valley (e.g., Martin et al. 2007). This is a region located between the red and blue cloud sequences, best identified in the NUV–r color–magnitude diagram, where SF activity is being actively quenched and galaxies are thought to be in transitional stage in their migration from the blue to the red sequence.

Most galaxies in our sample are either normal luminosity IR galaxies \((L_{12}\mu m \sim 10^{9.2-10} L_\odot; 60\%)\), low luminosity IR galaxies \((L_{12}\mu m < 10^{9.2} L_\odot; 31\%)\), or luminous infrared galaxies (LIRGs; \(L_{12}\mu m \sim 10^{10-10.8} L_\odot; 9\%\)). However, ULIRGs are also present. There are 114 objects with \(L_{12}\mu m > 10^{10.8} L_\odot\) (roughly equivalent to \(L_{TIR} > 10^{12} L_\odot\) using the conversion of Chary & Elbaz 2001), corresponding to a surface density of 0.049 deg\(^{-2}\). This is comparable to the 0.041 deg\(^{-2}\) surface density...
density found by Hou et al. (2009). These ULIRGs naturally lie at higher redshift ($z \approx 0.2$) and populate the massive end of the SF sequence above $\sim 10^{11} M_\odot$. We reiterate that these results come from matching WISE to the relatively bright SDSS spectroscopic sample. WISE galaxy populations down to $r \sim 22.6$ are analyzed in L. Yan et al. (2011, in preparation).

### 3.3. 12 $\mu$m Luminosity and Stellar Mass

We now have a large sample of 12 $\mu$m selected galaxies that range from low-IR to ULIRG luminosities, for which high-quality optical spectra and dust-corrected optical SFRs are available. First, we examine the relation between $L_{12 \mu m}$ and stellar mass. B04 have shown that, at least for SF systems, SFR and stellar mass are strongly correlated in the local universe. There is also evidence that this relationship evolves with redshift (Noeske et al. 2007, Daddi et al. 2007). Although it is expected that more massive galaxies are naturally more luminous, it is unclear whether more massive systems would have more dust emission in the mid-IR. Figure 4 shows the correlation between monochromatic 12 $\mu$m luminosity and stellar mass for our sample. The correlation is tight for SF systems over nearly three orders of magnitude in stellar mass (gray points, top panels). Several studies have found that the distributions of [O iii] emission line flux to the AGN continuum flux at X-ray, mid/far-IR, and radio wavelengths (i.e., where stellar emission and absorption by the torus are least significant) are very similar for both type I and type II AGNs (Mulchaey et al. 1994; Keel et al. 1994; Alonso-Herrero et al. 1997). Based on this, Kauffmann et al. (2003a) and Heckman et al. (2004) have shown that [O iii] flux is a reliable estimator of AGN activity. Following these works, we split the AGN sample by [O iii] luminosity. We see that strong AGNs ($L_{[\text{O iii}]} > 10^7 L_\odot$) have IR luminosities considerably larger than weak AGNs ($L_{[\text{O iii}]} < 10^7 L_\odot$), following approximately the same relationship with mass as SF systems. Weak AGNs, instead, lie well below that correlation and show a larger scatter. We note that the contribution by SF regions to the [O iii] flux is $<7\%$ (Kauffmann et al. 2003a).

In the right bottom panel of Figure 4, we compare the ages of stars in all subsamples as derived from the $D_{4000}$ spectral index. SF galaxies have the youngest stellar populations, peaking at $\sim 0.5$ Gyr, followed by considerably older composite galaxies ($\sim 1.5–2$ Gyr). Strong AGNs, which dominate the massive end, have intermediate stellar populations ($\sim 1.5$ Gyr) that are closer to SF/composite systems than to weak AGNs (see Figure 1). In contrast, weak AGNs tend to be hosted by early-type galaxies with significantly older stars ($\sim 3$ Gyr), as found also by Kauffmann et al. (2003a) after comparing AGN host sizes, surface densities, and concentration ratios with those of normal early-type galaxies. This highlights the importance that young/old stars have in powering the 12 $\mu$m emission. For AGNs of roughly similar stellar mass, only when younger stars begin to dominate (and the active nuclei becomes more powerful) is the IR emission comparable to actively SF systems. Qualitatively, the same result holds if we use the dust-corrected $r$-band absolute magnitude instead of stellar mass.
Figure 4. 12 μm infrared luminosity as a function of stellar mass for SF galaxies (gray), strong AGNs with \( L_{[\text{O}III]} > 10^7 L_\odot \) (color points, top left), and weak AGNs with \( L_{[\text{O}III]} < 10^7 L_\odot \) (color points, top right). The solid line shows the median \( L_{12\mu m} \) of SF galaxies as a function of mass. Bottom panels show the distribution of \( L_{12\mu m} \) and stellar age for the various populations as indicated.

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

Figure 5. Cumulative fraction of integrated 12 μm luminosity for galaxies dominated by stellar populations of a given age, separated according to spectral type as: SF galaxies (blue), composite systems (green), strong AGNs (black), and weak AGNs (red).

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

of the total IR luminosity is produced by galaxies younger than 0.6 Gyr. Composite galaxies and strong AGNs reach the same fraction at ages of 1.5 Gyr and 2 Gyr, respectively. In weak AGNs, instead, most of the mid-IR emission is produced within a range of ~1–3 Gyr. This inventory of 12 μm luminosity in the local universe shows where the bulk of the IR emission resides, shifting from stellar populations of a few hundred Myr in actively SF galaxies to a few Gyr in galaxies hosting weak AGNs. Thus, it underlines again the important role that young/old stars have in powering 12 μm emission. As we will see later in Section 3.6, this also supports the idea that transition galaxies (i.e., composite/strong AGNs) form a smooth sequence that joins highly active galaxies with quiescent galaxies.

3.4. 12 μm Luminosity and Star Formation Rate

We now explore the relationship between infrared luminosity and optical, dust-corrected SFR. Figure 6 shows \( L_{12\mu m} \) versus SFR\(_{opt}\), color coded by the \( D_{4000} \) spectral index. As discussed by Kauffmann et al. (2003b), the \( D_{4000} \) index is a good indicator of the mean age of the stellar population in a galaxy. The dashed line indicates the reference relation of Kennicutt (1998), as given by Chary & Elbaz (2001) in terms of 12 μm luminosity, to convert IR luminosity into “instantaneous” SFR. It was derived from simple theoretical models of stellar populations with ages 10–100 Myr without considering factors like metallicity or more complex star formation histories. While this makes it strictly valid only for young starbursts, the Kennicutt relation is quite often applied to the more general population of SF galaxies. Figure 6 shows that the IR emission from SF galaxies (left panel) correlates fairly well with SFR\(_{opt}\). The correlation is tighter for
high SFRs, becoming broader and slightly asymmetric for low SFRs. A least-squares fit to the SF sample is given by

$$\log L_{12,\mu m} = (0.987 \pm 0.002) \log SFR_{opt} + (8.962 \pm 0.003).$$  \hspace{1cm} (1)$$

This expression is close to the Chary & Elbaz (2001) relation at high SFRs, which is not surprising given that this relation was calibrated using the IRAS Bright Galaxy Sample (Soifer et al. 1987), i.e., luminous galaxies with $L_{12,\mu m} > 10^9 L_\odot$. The small differences are likely attributable to luminosity/redshift selection effects and the slight differences between ISO and WISE 12 $\mu m$ filters. More importantly, the agreement is quite good considering the different (FIR versus optical emission lines) of the SFRs. Relative to the Chary & Elbaz (2001) conversion, $L_{12,\mu m}$ is comparatively suppressed by a factor $>1.6$ for $SFR_{opt} \sim 0.1 M_\odot$ yr$^{-1}$. This is likely because low SFR systems have very low stellar masses ($<10^9 M_\odot$), and therefore become more transparent due to the increasing fraction of stellar light that escapes unabsorbed by dust. We note, however, that the spatial distribution of dust in H II regions and/or molecular clouds could also have influence (e.g., Leisawitz & Hauser 1988). In addition, we have repeated the test for the bluest galaxies in the SF galaxy class, obtaining no significant differences. This suggests that other effects like metallicity could also be relevant.

For AGNs, the coupling between optical SF and IR luminosity follows a different relationship (right panel of Figure 6). Most AGNs lie in a broader distribution above the instantaneous conversion of Kennicutt, particularly those with $SFR_{opt}$ below $\sim 1 M_\odot$ yr$^{-1}$. For a fixed SFR, the IR emission is higher by a factor of several relative to SF galaxies, suggesting that $L_{12,\mu m}$ is not driven by the current SF for most AGNs. Weak AGNs are predominantly associated with massive, early-type galaxies increasingly dominated by old stars at low SFRs ($\sim 0.1 M_\odot$ yr$^{-1}$). Given their red optical colors, it is unlikely that recent SF could be responsible for their IR emission. More likely, dust grains heated due to older stars or an AGN are driving this emission. Note, however, that in Section 3.8 we will show that the contribution of AGNs at 12 $\mu m$ is of minor importance for most AGNs, except perhaps for the most powerful ones. Only strong AGNs, which are dominated by intermediate-to-young stellar populations, tend to occupy a region similar to SF galaxies in Figure 6. They show a clear “excess” in $L_{12,\mu m}$ at $SFR_{opt} \sim 0.5 M_\odot$ yr$^{-1}$ that gradually decreases when stars get younger toward higher SFRs. This shows that the age of stars in an AGN is an important factor in determining the origin of the 12 $\mu m$ emission. An expression fitting AGNs (weak and strong) is given by

$$\log L_{12,\mu m} = (0.582 \pm 0.004) \log SFR_{opt} + (9.477 \pm 0.002).$$  \hspace{1cm} (2)$$

Recent work by Salim et al. (2009) compared NUV/optical SFRs with $L_{4000}$ calibrated from 24 $\mu m$ fluxes for red- and green-sequence objects at $z \sim 0.7$ (corresponding to rest-frame 14 $\mu m$, close to the WISE 12 $\mu m$ band). They find large excess IR emission for a given SFR, attributed mainly to older stellar populations, and to a lesser extent to an AGN. We find broadly consistent results, but for 12 $\mu m$ selected AGN sources with optical SFRs. Kelson & Holden (2010) have suggested that thermally pulsating asymptotic giant branch (TP-AGB) carbon stars with ages of 0.2–1.5 Gyr (corresponding to $D_{4000} \sim 1.2–1.5$) can also contribute significantly to the mid-IR flux. As seen in Section 3.3, this does not seem to be important for our much older, weak AGNs, and perhaps marginally relevant in strong AGNs that have typical stellar ages slightly above the upper 1.5 Gyr limit. The case of SF galaxies is interesting because most of the 12 $\mu m$ luminosity seems to originate from galaxies in the $\sim 0.3$–0.6 Gyr age range and this luminosity correlates relatively well with the optical SFR. While the age ranges seems to overlap, it is difficult to prove whether TP-AGB dominate the emission or not. Further SED decomposition and modeling of stellar populations is required to find the fraction of mid-IR luminosity powered by TP-AGB stars, a task that is potentially complicated by metallicity effects and uncertainties in the ensemble colors of such stars. However, the general picture is consistent with previous results (Salim et al. 2009; Kelson & Holden 2010) that find evidence for the
mid-IR being sensitive to star formation over relatively long (>1.5 Gyr) timescales.

Finally, we consider composite systems, which present considerable SF activity along with spectral signatures of an AGN (middle panel of Figure 6). By definition, these objects have up to 40% (see B04) of their Hα emission coming from a nonstellar origin, though the fraction is <15% for most galaxies. With masses, ages, and optical colors intermediate between the SF and AGN sequences, composite galaxies closely follow the Kennicutt relation, except at the low SFR end where older stars once again begin to dominate. A least-squares fit for composite galaxies has a slope intermediate between AGNs and SF galaxies, and is given by

$$\log L_{12\mu m} = (0.671 \pm 0.003) \log \text{SFR}_{\text{opt}} + (9.249 \pm 0.002).$$

(3)

We note that the optical SFRs utilized here, while not ideal, are probably the best estimates publicly available for such a large and diverse population of galaxies in the local universe. Other methodologies that use more sophisticated dust corrections and employ H2, FIR, or radio data could provide more accurate values, but are difficult to apply across the entire sample and data are not always available (see Saintonge et al. 2011 for a values, but are difficult to apply across the entire sample and

We have verified that the SDSS SFRs in our sample are in broad agreement with UV-based SFRs derived by Salim et al. (2007) (S. Salim 2011, private communication), with an average scatter of 0.055/0.387 for the total sample (0.013/0.334 for strong AGNs and 0.242/0.567 for weak AGNs).

3.5. 22 μm Luminosity and Star Formation Rate

WISE is less sensitive at 22 μm than at 12 μm, but a significant fraction of our sample (~30%) has measured 22 μm fluxes above 5 mJy (note we find no 22 μm galaxies without 12 μm detection). Similar to the 12 μm sample, this 22 μm subsample is a mixture comprised of 65% SF galaxies, 14% AGNs, and 19% composite systems. However, the fraction of strong AGNs is 38%, compared to 16% for 12 μm sources. As 22 μm is closer to the dust emission peak and is not affected by polycyclic aromatic hydrocarbon (PAH) emission features, it is interesting to compare with the 12 μm galaxies of our previous analysis. Figure 6 shows the linear fits for the 22 μm subsample (triangle markers). These relations are very similar to the 12 μm fits (solid line for SF galaxies, square markers for AGNs, and composite galaxies) supporting the independence of our results on the particularities of a single mid-IR band.

3.6. Specific Star Formation Rate

Given the strong correlations between optical or IR light and stellar mass, a more interesting metric for comparison is the SSFR or SFR/$M_\odot$, that measures the current relative to past SFR needed to build-up the stellar mass of the galaxy. The SSFR traces the star formation efficiency and its inverse defines the timescale for galaxy formation or the time the galaxy required to build-up its current mass. Higher values of SSFR are indicative of a larger fraction of stars being formed recently. While ideally we would use gas mass or total mass instead of stellar mass for the normalization, such masses are not easily measured.

Figure 7 shows the SSFR as a function of 12 μm luminosity for the different galaxy classes. The nearly flat correlation for SF galaxies means that no matter the IR output, the amount of star formation per unit mass remains relatively constant. SF galaxies display a weak dependence with $L_{12\mu m}$ that gets narrower toward higher luminosities. As noted before, a possible origin for such residual SSFR could be due to a metallicity gradient. Calzetti et al. (2007) studied individual SF regions of fixed aperture in nearby galaxies with known Paα surface density and found that low metallicity galaxies have a small deficit in $24\mu m$ emission compared to high metallicity galaxies. Relaño et al. (2007) confirmed that while $24\mu m$ luminosity is a good metallicity-independent tracer for the SFR of individual H II regions, the metallicity effect should be taken into account when analyzing SFRs integrated over the whole galaxy. We test qualitatively for a metallicity effect by calculating the SFR per unit mass per unit metallicity, where the metallicity is given by the $12 + \log(O/H)$ gas-phase oxygen abundance derived from optical nebular emission lines. The SF population displays an almost perfectly flat relationship over almost four orders of magnitude in $L_{12\mu m}$ such that independent of IR output, a galaxy of given mass and metal content converts gas into stars at a nearly constant rate. We note that these metallicities represent the current metal abundance rather than the luminosity-weighted average of past stellar populations. They also do not suffer from complications due to α-element enhancement or age uncertainties, characteristic of methods relying on absorption-line indices. Bond et al. (2012) arrive at a similar conclusion regarding a constant SSFR in nearby galaxies using Herschel 250 μm and WISE 3.4 μm data.

Compared to SF galaxies, AGNs have SSFRs lower by a factor of ~10, mainly because of their higher stellar masses. However, strong AGNs lie much closer to the SF sequence than weak AGNs. The former are hosted by high stellar mass galaxies, but also have young stellar populations that drive up the SFR at high $L_{12\mu m}$. Weak AGNs do not have this boost in SFR and hence have lower SSFRs. Once again, composite systems populate a region intermediate between SF galaxies and strong AGNs. Previous studies (e.g., Brinchmann et al. 2004; Salim et al. 2007) have shown the relationship between the SFR and $M_*$, identifying two different sequences: galaxies on an SF sequence and galaxies with little or no detectable SF. While the
3.7. SSFR Dependence on Mid-IR Color

Recent work on resolved nearby galaxies has shown a definite correlation between IR color and luminosity. Y. Shi et al. (2011, in preparation) found that for a variety of sources ranging from ULIRGs to blue compact dwarf galaxies, the flux ratio \( f_{24 \mu m} / f_{8.8 \mu m} \) traces the SSFR and also correlates with the compactness of SF regions. While ideally we would like to know the SFR surface density, we first explore the relation between SSFR and 4.6–12 \( \mu m \) galaxy color, as shown in Figure 8. Galaxies from the main SF sequence (blue contours) correlate strongly with IR color, with strong AGNs (black contours) continuing the trend at bluer colors. Weak AGNs extend (red contours) that relationship remarkably well toward the low star formation end, albeit with higher dispersion and a slightly steeper slope. Hence, for the same increase in SSFR, AGNs experience a smaller variation in IR color than typical SF objects. This is probably due to the combination of a metallicity effect and the different stellar populations that regulate the IR emission budget. In any case, this suggests that the higher the SSFR, the more prominent the 12 \( \mu m \) IR emission becomes relative to 4.6 \( \mu m \), where the latter is expected to strongly correlate with stellar mass. This shows that the 4.6–12 \( \mu m \) color serves well as a rough first-order indicator of star formation activity over three orders of magnitude in SFR. A simple expression fitting all galaxies is given by

\[
\log \text{SSFR} = (0.775 \pm 0.002)(W2 - W3)_0 - (12.561 \pm 0.006).
\]

(4)

If the galaxy is known to host an AGN, then the more accurate expression is

\[
\log \text{SSFR} = (0.840 \pm 0.008)(W2 - W3)_0 - (12.991 \pm 0.020).
\]

(5)

These results show that there is a tight link between stellar mass, current SFR, and IR color in SF galaxies, which emphasizes the role of the dominant stellar population in regulating star formation.

3.8. Effect of AGNs on the Energy Budget

In the previous sections we noted that the emission from the AGN could have a significant effect on the IR emission, and potentially bias the luminosities of the AGN galaxy class. This could be particularly important for low SFR galaxies. We test for this effect by estimating the contribution of the AGN to the total energy budget for sources classified from the BPT diagram as either an AGN or as an SF galaxy. To do so, we analyze the fraction of the 12 \( \mu m \) luminosity contributed by each of the four templates used in the SED fitting process to our optical+IR photometry, paying particular attention to the AGN component. Figure 9 shows the median fraction of 12 \( \mu m \) luminosity contributed by each template, for objects classified as SF galaxies. The majority of the power is split among
Figure 10. Same as Figure 9, but for objects classified as weak AGNs (dashed) and strong AGNs (solid).

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

The irregular (Im), spiral (Sbc), and elliptical (E) templates, though the AGN contribution becomes significant for the most luminous sources, above $10^{10.8} L_\odot$. This implies that the AGN has a negligible influence in SF galaxies. Figure 10 shows these fractions for weak and strong AGN galaxy classes. The elliptical component is now more prominent in weak AGNs of low luminosity, which is not unexpected. In general, the AGN component is now more important but is still far from contributing significantly below $10^{10.8} L_\odot$. In most weak AGNs (~80%), the AGN contribution to the 12 μm luminosity is below 40%. About 70% of strong AGNs show similar low AGN contributions at 12 μm. We note that in Figure 10 we used WISE aperture photometry for extended, nearby sources and profile-fitting magnitudes for unresolved galaxies with $\chi^2 < 3$ (see Section 4.5 of WISE Preliminary Release Explanatory Supplement for further details). Although the differences are small, aperture photometry improves the quality of the SED fit of low luminosity galaxies, as it captures the more extended flux of objects at low redshifts.

Note that in both cases, SF galaxies and AGNs, the emission is dominated by the spiral (Sbc) component, which has a relatively high mid-IR SED. This is because the template, originally constructed from Coleman et al. (1980) and extended into the UV and IR with Bruzual & Charlot (2003) synthesis models, also considers emission in the mid-IR from dust and PAHs.

These are added by ad hoc linear combinations of appropriate parts of NGC 4429 and M82 SEDs obtained by Devriendt et al. (1999). Figure 11 shows the SED fit for AGNs with luminosities of $L_{[\text{Oiii}]} \sim 10^6 L_\odot$ and $L_{[\text{Oiii}]} \sim 10^7 L_\odot$. In each case we plot the object with the median $\chi^2$, i.e., the typical fit for sources of those luminosities. The nine photometric bands are well fitted by the model in most cases. For AGNs with $L_{[\text{Oiii}]} > 10^{7.5} L_\odot$ we find the SED fit is reasonably good (although in general with higher $\chi^2$) except at the 22 μm band. We believe this is caused by the limitation of the algorithm (not the templates themselves) to properly fit highly reddened AGNs fainter than their hosts, as it is designed to punish the excessive use of reddening on the AGN when few relevant data points are used. Modifying the algorithm slightly to remove this behavior, we are able to obtain fits with better $\chi^2$ values for these objects assigning much higher AGN fractions and reddening values, yet the lack of farther IR data to determine the origin of the 22 μm excess makes these numbers also uncertain. Therefore, while these results do not definitely rule out that the central AGN could have a considerable effect in some extreme sources (e.g., the very strong AGN), it certainly shows that they are not relevant for most of the galaxy populations analyzed in this paper.

4. SUMMARY

In this work, we have taken advantage of recently released data from WISE and SDSS to construct the largest IR–optical sample of galaxies with 12 μm fluxes and optical spectra available at $z \sim 0.1$. This sample allowed us to investigate with high statistical significance how physical parameters such as color, stellar mass, metallicity, redshift, and SFR of 12 μm selected galaxies compare with purely optically selected samples. We have quantified how the SFR estimates compare for the different spectral types as a function of stellar mass, galaxy age, and IR color in order to pinpoint the underlying source of 12 μm emission and therefore up to what extent it could be interpreted as a useful SFR indicator.

The main results of this paper can be summarized as follows.

1. In general, the WISE–SDSS 12 μm selected galaxy population traces the blue, late-type, low-mass sequence of the bimodal galaxy distribution in the local universe. It also traces intermediate-type objects with active nuclei, avoiding the bulk of the red and “dead” galaxies without emission...
2. The IR emission of SF galaxies and strong AGNs, dominated by the blue, young stellar population component, is well correlated with the optical SFR. There is a small tendency of low SFR systems to have slightly lower IR luminosity when compared to the canonical relation of Charry & Elbaz (2001). These are low SFR, low-mass systems that likely become more transparent due to the increasing fraction of light that escapes unabsorbed and hence supresses $L_{12\mu m}$. However, other effects like the dust distribution or metallicity could be relevant as well. The latter is shown by the (weak) SSFR dependence on $L_{12\mu m}$. In general, the mid-IR emission at $22\mu m$ follows similar correlations seen for the $12\mu m$ selected sample, suggesting that these results do not critically depend on a single IR band.

3. SF galaxies are forming stars at an approximately constant rate per unit mass for an IR output ranging over five orders of magnitude. There is a small tendency for more luminous objects to have enhanced SSFR, which could be interpreted as a sign of SF histories peaking toward later times. However, this residual dependence seems to be caused by a metallicity gradient. Once factored out, the relationship becomes nearly flat. Strong AGNs behave as a continuation at the massive end of the normal SF sequence, where the AGNs (possibly after a starburst episode) gradually quench SF and weaken as they consume the gas available, with the mid-IR emission fading in consequence.

4. The mid-IR 4.6–12 $\mu m$ rest-frame color can be used as a first-order indicator of the overall SF activity in a galaxy, as it correlates well with the SSFR. For increasing SFR/$M^*$, the IR emission becomes more prominent at $12\mu m$ (associated with dust emission) relative to 4.6 $\mu m$ (associated with stellar mass).

5. For the case of SF galaxies, most of the mid-IR luminosity distribution is concentrated in systems younger than $\sim$0.5 Gyr. Redder galaxies are dominated by older stellar populations, which contribute increasingly to the $12\mu m$ emission. While many of these galaxies host an AGN (usually weak) the $12\mu m$ energy budget is generally not dominated by the central active nuclei. This might well not be the case of bright galaxies with very strong active nuclei ($L_{[10\mu m]} > 10^5.5 L_{[60]}$) where a considerably larger fraction of mid-IR emission could be due to the AGN. Spatially resolved, longer wavelength IR data and further modeling is necessary to fully understand these sources.

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