THE WYOMING SURVEY FOR Hα. III. A MULTI-WAVELENGTH LOOK AT ATTENUATION BY DUST IN GALAXIES OUT TO z ∼ 0.4

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ABSTRACT

We report results from the Wyoming Survey for Hα (WySH), a comprehensive four-square degree survey to probe the evolution of star-forming galaxies over the latter half of the age of the universe. We have supplemented the Hα data from WySH with infrared data from the Spitzer Wide-area Infrared Extragalactic Survey and ultraviolet data from the Galaxy Evolution Explorer Deep Imaging Survey. This data set provides a multi-wavelength look at the evolution of the attenuation by dust, and here we compare a traditional measure of dust attenuation (L(TIR)/L(FUV)) to a diagnostic based on a recently developed robust star formation rate (SFR) indicator, [Hα/obs. + 24 μm]/Hα/obs. With such data over multiple epochs, the evolution in the attenuation by dust with redshift can be assessed. We present results from the ELAIS-N1 and Lockman Hole regions at z ∼ 0.16, 0.24, 0.32, and 0.40. While the ensemble averages of both diagnostics are relatively constant from epoch to epoch, each epoch individually exhibits a larger attenuation by dust for higher SFRs. Hence, an epoch-to-epoch comparison at a fixed SFR suggests a mild decrease in dust attenuation with redshift.

Key words: dust, extinction – evolution – galaxies: general

Online-only material: color figures

1. INTRODUCTION

A fundamental property of a galaxy is the number of stars it gives birth to each year, commonly known as its star formation rate (SFR). Likewise, the average number of stars forming per year per cubic megaparsec, the cosmic star formation rate density (SFRD), is a key parameter in the study of galaxy evolution. To quantify these fundamental parameters, a number of different SFR indicators are used, and they stem from a wide range of wavelengths. The SFR can be estimated using the density (SFRD), is a key parameter in the study of galaxy evolution. To quantify these fundamental parameters, a number of different SFR indicators are used, and they stem from a wide range of wavelengths. The SFR can be estimated using the

and the differential impacts of metallicity and the ionization state of the gas on the various SFR indicators (Kennicutt 1998; Xu et al. 2003; Choi et al. 2006; Salim et al. 2007; Linares-López et al. 2009). While many of these discrepancies are due to the uncertainties in the conversion factors from luminosities to SFRs, an additional possibility for discrepancy exists within the different survey selection criteria (Trevese et al. 2002; Buat et al. 2007b). More “robust” SFR measures have recently been devised using a combination of IR + UV data or IR + Hα data (Hirashita et al. 2003; Calzetti et al. 2007; Kennicutt et al. 2007, 2009; Prescott et al. 2007; and references therein) because the IR emission traces extinguished starlight, while the UV and Hα emission trace relatively unextinguished starlight. These SFR indicators have been used in a large number of surveys to map the cosmic SFR at a variety of redshifts (e.g., Cowie et al. 2004; Le Floc’h et al. 2005; Doherty et al. 2006; Dale et al. 2008; Prescott et al. 2009). The cumulative result of these efforts shows that the cosmic SFRD has significantly evolved over the last several gigayears, perhaps by as much as a factor of 10 between z ∼ 1 and the present epoch (e.g., Watson et al. 2009). Therefore, it is not surprising that the galaxies we observe locally do not necessarily resemble those at higher redshifts (Pei et al. 1999; Davies et al. 2009). For example, Luminous Infrared Galaxies (LIRGs) and Ultra-Luminous Infrared Galaxies (ULIRGs) are increasingly important as we look back to redshifts of z ∼ 1 – 2 as both the IR and UV luminosity functions evolve toward a predominance of LIRGs at higher z (Papovich et al. 2006; Reddy et al. 2006, 2008; Buat et al. 2009; Salim et al. 2009). These dusty objects come to dominate the luminosity of the galaxy population as we move toward higher redshifts. Does this effect lead to a change in the average amount of obscuration by dust over time? Does the buildup of metal content within galaxies as they age strongly affect their extinction by dust (e.g., Mannucci et al. 2009)? Not only do galaxies evolve with redshift, they each evolve on their
own timescales (i.e., they run out of gas and cease to form stars, they are involved in mergers with other galaxies, etc.). These changes imply that the light that is detected from a given galaxy will be a function not only of its redshift, but also a function of parameters such as metallicity, star formation history, merger stage (if applicable), and the relative luminosity dominance of any supermassive black hole (Kennicutt 1998; Calzetti & Heckman 1999; Pei et al. 1999; Jansen et al. 2001; Dale et al. 2007; Wu et al. 2007; Engelbracht et al. 2008, and references therein).

Not only do SFR indicators tell us how many stars are being formed, but also they can provide other physical insight when two different SFR indicators are coupled together. For example, the IR-to-UV ratio is typically used to measure the amount of dust attenuation at UV wavelengths. Studies coupling IR and UV data have shown that the slope of the UV continuum is a useful probe of the attenuation by dust in starburst galaxies (Calzetti et al. 1994; Meurer et al. 1999), so simply tracking the IR-to-UV ratio with the look-back time should prove fruitful. Recent efforts, however, lead to a confusing set of divergent results. Evidence from (rest-frame) UV-selected surveys by Buat et al. (2007b), Burgarella et al. (2007), and Reddy et al. (2006) at \( z \sim 0, 1, \) and 2, respectively, shows that the average dust attenuation within galaxies decreases with increasing redshift. Similar results were reported by Buat et al. (2007a) and Xu et al. (2007) for LIRGs. This is the expected result if the dust within galaxies slowly builds up as the effects of generations of stellar lifecycles accumulate over time. However, Le Floc’h et al. (2005) find that the comoving IR energy density for an IR-selected sample evolves as \( (1 + z)^{3.9} \) at \( 0 < z < 1 \), whereas the UV only evolves as \( (1 + z)^{2.5} \) over the same span in redshift (Schiminovich et al. 2005). Takeuchi et al. (2005), using the same data set as Le Floc’h et al. (2005), report a similar result over the same range in redshift. While the Le Floc’h et al. (2005) and Schiminovich et al. (2005) results are based on samples of galaxies that are likely very different, together, they could imply that the average UV attenuation by dust within galaxies increases with the look-back time. This result would be counterintuitive if dust attenuation were only governed by metal abundance. However, the result is understandable if the attenuation by dust increases with SFR (e.g., Wang & Heckman 1996; Heckman et al. 1998; Calzetti 2001; Hopkins et al. 2001b) and the cosmic SFRD increases with the look-back time. Finally, a third possible result is reported by Bell et al. (2005), Choi et al. (2006), Xu et al. (2007), and Zheng et al. (2007) who find dust attenuation values at higher redshifts (\( 0.6 < z < 0.8 \)) consistent with those found in the current epoch. However, it should be noted that all of these studies utilize some sort of IR selection. While not all of the studies using an IR selection come to this same conclusion, this possible selection effect should be looked at in more depth.

Buat et al. (2007b) have shown that UV and IR surveys of the nearby universe do not necessarily sample the same galaxy populations, and thus the above discrepancies may be in part due to sample selection. The UV continuum traces the SFR on a timescale of \( \sim 10^7 \) yr (e.g., Iglesias-Páramo et al. 2004), while the IR continuum traces SFRs on a timescale of \( \sim 10^8 \) yr (e.g., Kennicutt 1998). This, as well as issues such as feedback from SFR evolution, Lyman \( \alpha \) absorption, the evolution of dust grains, and the evolution of the average dust temperature, can all affect the IR and UV luminosities. Invoking data from a large, uniform \( \text{H} \alpha \)-selected survey could help to clear this confusion (Iglesias-Páramo et al. 2004). \( \text{H} \alpha \) emission traces SFRs on a timescale of \( \lesssim 10^7 \) yr (e.g., Iglesias-Páramo et al. 2004) making it an ideal comparison to the IR continuum. Focusing just on this similarity in timescales, and ignoring evolutionary processes such as the dispersal of dust grains into the interstellar medium (ISM), the ratio of \( \text{H} \alpha \) to IR should remain relatively constant over time within a galaxy. Recent work from the Spitzer Infrared Nearby Galaxy Survey (SINGS) finds that the \( \text{H} \alpha + 24 \mu \text{m} \) data have an almost one-to-one correlation with that of extinction-corrected Paschen \( \alpha \), considered an ideal SFR indicator as it directly traces \( \text{H} \) II regions and lies at a relatively long wavelength to help minimize the effects of obscuration by dust (Calzetti et al. 2007; Kennicutt et al. 2007; Prescott et al. 2007, see Figure 11 in Calzetti et al. 2007). This \( \text{H} \alpha + 24 \mu \text{m} \)-based SFR indicator can be compared to the more commonly used indicator, \( L(\text{H} \alpha) \) alone (Kennicutt 1998) to form a diagnostic sensitive to the amount of attenuation by dust within galaxies, a multi-wavelength diagnostic where all the inputs conveniently trace star formation (SF) on the same timescale. Although recent results from Kennicutt et al. (2009) indicate that it can be just as effective to use a combination of the total infrared (TIR) emission + \( \text{H} \alpha \) or 8 \( \mu \text{m} + \text{H} \alpha \), TIR data are not frequently available for surveys of distant galaxies and 8 \( \mu \text{m} \) data may be more problematic due to the variable nature of polycyclic aromatic hydrocarbon (PAH) emission with radiation field hardness and metallicity (Engelbracht et al. 2005; Madden et al. 2006; O’Halloran et al. 2006; Rosenberg et al. 2006; Wu et al. 2006; Dale et al. 2009a).

The Wyoming Survey for \( \text{H} \alpha \) (WySH) is a large-area, ground-based, narrowband optical imaging survey for \( \text{H} \alpha \) at redshifts \( z \sim 0.16, 0.24, 0.32, \) and 0.40 (Dale et al. 2008). In addition, this effort is being supplemented by the NEWFIRM Narrowband Hα Survey, a collaborative near-IR imaging survey of \( \text{H} \alpha \) at redshifts of \( z \sim 0.81 \) and 2.2 (Lee et al. 2009; J. C. Lee et al. 2010, in preparation; C. Ly et al. 2010, in preparation). Both surveys target key extragalactic deep fields where an abundance of multi-wavelength imaging and spectroscopy are already available. In this work, we utilize \( \left(H_\alpha \text{obs} + 24 \mu \text{m})/H_\alpha \text{obs}\right) \) to directly gauge the amount of attenuation by dust in a large sample of galaxies that span redshifts out to \( z \sim 0.4 \). Our main goal is to robustly measure any changes in the average dust attenuation over cosmic time. Secondary goals include comparing the relatively new technique for assessing the attenuation by dust, by combining \( \text{H} \alpha \) and 24 \( \mu \text{m} \), with schemes based on the coupling of IR and UV.

In this paper, we outline the data sets used in Section 2, present the analysis and initial results from \( z \sim 0.16, 0.24, 0.32, \) and 0.40 in Section 3, and summarize our findings in Section 4. The cosmology used throughout this paper is \( H_0 = 70 \text{h} \text{Mpc}^{-1} \), \( \Omega_m = 0.3 \), and \( \Omega_k = 0.7 \).

2. DATA

2.1. Fields

Results for the ELAIS-N1 (\( \alpha \sim 16^h11^m, \delta \sim +55^\circ00^\prime \)) and Lockman Hole (\( \alpha \sim 10^h45^m, \delta \sim +58^\circ00^\prime \)) regions are presented here. These regions are popular targets for deep extragalactic surveys since they are comparatively free of contamination by zodiacal and Galactic dust (\( I_c(100 \mu \text{m}) \sim 1 \text{MJy sr}^{-1} \)), as well as by bright stars and nearby galaxies. Two relevant surveys carried out in ELAIS-N1 and the Lockman Hole are the Spitzer Wide-Area Infrared Extragalactic (SWIRE) Survey (see Section 2.2.2) and the Galaxy Evolution Explorer (GALEX) Deep Imaging Survey (see Section 2.2.3). Some 30 separate 18 fields were targeted by the WySH program in these two fields.
and 2 at the Kitt Peak National Observatory 4 m telescope at survey is being supplemented with collaborative near-IR work \(\sim z\) the Wyoming Infrared Observatory (WIRO) 2.3 m telescope are filter to subtract the continuum. The epochs being observed at improved continuum subtraction, relative to using a broadband of approximately 1 (A color version of this figure is available in the online journal.)

6 http://newfirm.ociw.edu/wiki/Main_Page

Table 1
WySH Optical Imaging and Source Counts

| \(z\) | ELAIS-N1 (\(\square\)) | Lockman Hole (\(\square\)) | NB Int. Time (s) | No. of H\(\alpha\)* | No. of H\(\alpha\) + 24 \(\mu\)m* | No. of H\(\alpha\) + 24 \(\mu\)m + UV* |
|-------|----------------------|---------------------|-----------------|-----------------|-----------------|-----------------|
| 0.16  | 1.38                 | 1.01                | 1200            | 94              | 43              | 39              |
| 0.24  | 1.35                 | 0.83                | 3600            | 239             | 69              | 62              |
| 0.32  | 1.33                 | 0.87                | 6000            | 250             | 82              | 67              |
| 0.40  | 0.52                 | 0.00                | 9600            | 49              | 20              | 16              |
| Total | \(\ldots\)           | \(\ldots\)          | \(\ldots\)      | 632             | 214             | 184             |

Notes.
* Detections from WySH are above 3\(\sigma\).
* Detections from SWIRE are above 5\(\sigma\).
* Detections from GALEX are above 5\(\sigma\).

(see Figures 1 and 2). Table 1 summarizes the total coverage at each epoch for both fields.

2.2. Data Sets
2.2.1. H\(\alpha\)

WySH is a \(\sim 4\) deg\(^2\), ground-based, narrowband imaging survey for H\(\alpha\) emitting galaxies over the latter half of the age of the universe. WySH uses a pair of wavelength-adjacent narrowband filters at each redshift epoch (for \(z \lesssim 0.40\)) for improved continuum subtraction, relative to using a broadband filter to subtract the continuum. The epochs being observed at the Wyoming Infrared Observatory (WIRO) 2.3 m telescope are \(z \sim 0.16, 0.24, 0.32\), and 0.40 (Dale et al. 2008). This optical survey is being supplemented with collaborative near-IR work at the Kitt Peak National Observatory 4 m telescope at \(z \sim 0.81\) and 2.2 by the NEWFIRM Narrowband H\(\alpha\) Survey,\(^6\) which is observing through low airglow windows at 1.19 and 2.10 \(\mu\)m (J. C. Lee et al. 2010, in preparation; C. Ly et al. 2010, in preparation). These data are being used to constrain the cosmic SFRD out to \(z \sim 2.2\). WySH data are sensitive down to a 3\(\sigma\) survey depth of \(\lesssim 1 M_{\odot}\) yr\(^{-1}\) for \(z \sim 0.16, 0.24, 0.32\), and 0.40, using the Kennicutt (1998) equation to convert from \(L(H\alpha)\) to SFR(H\(\alpha\)). This value has not been corrected for dust attenuation. For a full description of the optical survey and preliminary results for the SFRD and luminosity function at \(z \sim 0.16, 0.24, 0.32\), and 0.40, see Dale et al. (2008, 2010).

2.2.2. Infrared

SWIRE (Lonsdale et al. 2003), one of the Spitzer Legacy Projects, was designed to image \(\sim 49\) deg\(^2\) of the sky, as well as detect very distant galaxies (out to \(z \sim 3\)) in order to look at different properties of galaxy (and star) formation and evolution.\(^7\) SWIRE uses all seven imaging bands on Spitzer (3.6, 4.5, 5.8, and 8.0 \(\mu\)m with IRAC and 24, 70, and 160 \(\mu\)m with MIPS). Using the Calzetti et al. (2007) relation between \(N_{\nu}L_{\nu}\) and SFR,

\[
SFR(M_{\odot}\text{yr}^{-1}) = 1.27 \times 10^{-38}[\nu L_{\nu}(24\mu\text{m})(\text{erg s}^{-1})]^{0.8850},
\]

we find that, for a 3\(\sigma\) 24 \(\mu\)m survey depth of 135 \(\mu\)Jy, at \(z \sim 0.16, 0.24, 0.32\), and 0.40, galaxies with SFRs of approximately 0.22, 0.50, 0.86, and 1.4 \(M_{\odot}\) yr\(^{-1}\) (respectively) can be detected. The SWIRE Survey covers 9.2 deg\(^2\) in the ELAIS-N1 field and 11 deg\(^2\) in the Lockman Hole field (see Figures 1 and 2).

\(^6\) http://newfirm.ociw.edu/wiki/Main_Page

\(^7\) http://www.ipac.caltech.edu/SWIRE/
2.2.3. Ultraviolet

GALEX (Martin et al. 2005) is a space-based mission designed to study the UV properties of galaxies in the local universe.8 Utilizing both the far- and near-UV (FUV, NUV) detectors (1538.6 Å and 2315.7 Å, and FWHMs of 269 Å and 616 Å, respectively), the Deep Imaging Survey pointings have exposure times of 30 ks, as opposed to the 0.1 ks exposure times per pointing for the GALEX All-Sky Survey. Deep Imaging Survey pointings include ELAIS-N1 and the Lockman Hole. The Deep Imaging Survey has 5σ limiting magnitudes (in $m_{NUV}$) of $m_{NUV} = 24.4$ and $m_{FUV} = 24.8$, angular resolutions of 5′′ (NUV) and 4′′ (FUV), and sample galaxies with an average redshift of $z = 0.85$ (Martin et al. 2005; Morrissey et al. 2007).

Using the FUV limiting magnitude and the Kennicutt (1998) relation between UV luminosity and SFR, we find that, for a 5σ survey depth of $F_\nu = 4.365 \times 10^{-33}$ W m$^{-2}$ Hz$^{-1}$, at $z \sim 0.16, 0.24, 0.32,$ and 0.40, SFRs of approximately 0.04, 0.11, 0.20, and 0.35 $M_\odot$ yr$^{-1}$ (respectively) can be detected (assuming no attenuation by dust). It is also important to note that the GALEX Deep Imaging Survey is confusion limited and that standard pipeline results are not reliable for faint ($m_{NUV} > 23$ mag) sources (Burgarella et al. 2007; Martin et al. 2007; Zamoiski et al. 2007). This may slightly underestimate dust attenuation using the $vL_v (24\mu m)/vL_v (FUV)$ indicator for the UV faint galaxies. These UV faint galaxies follow the same trend as the brighter ($m_{NUV} < 23$ mag) UV galaxies, and make up ~8% of the entire sample ([0, 5, 8, 2] sources at $z \sim [0.16, 0.24, 0.32, 0.40]$). For the joint WySH/GALEX Deep Imaging Survey analysis carried out here, a total of 12 ~ 1° fields covering the ELAIS-N1 region and 18 ~ 1° fields covering the Lockman Hole region (see Figures 1 and 2) are used.

2.2.4. Merged Catalog

The Hα data from WySH were used for the initial sample selection, providing a sample of 94 + 239 + 250 + 49 galaxies at $z \sim 0.16, 0.24, 0.32,$ and 0.40, respectively, based on a 3σ detection limit. These data were first merged with a separate 24 μm SWIRE catalog with a depth of 3σ. Then, using the GATOR tool9 (provided through the NASA/IPAC Infrared Science Archive, IRSAA, the 2005 Spring SWIRE Spitzer catalogs for both the ELAIS-N1 and the Lockman Hole fields were accessed. These catalogs contain data in the four IRAC bands, as well as the MIPS 24 μm band. All sources in the catalog contain 3.6 μm and 4.5 μm data, but not all sources were detected at the necessary level in the remaining bands. In GATOR, we uploaded the WySH source coordinates separately for each epoch ($z \sim 0.16, 0.24, 0.32,$ and 0.40), and searched for coordinate matches with SWIRE sources within a 3′′ radius to create a WySH + SWIRE database. To create the WySH + SWIRE + GALEX merged catalog of sources, the WySH + SWIRE catalogs were coordinate matched with the GALEX catalogs from GALEX Release 5 (GR5) using a search radius of 3′. The distance between any two Hα sources is larger than the point-spread functions (PSFs) of both Spitzer and GALEX, so the ~6′ resolution of MIPS24 and GALEX imaging usually does not result in multiple galaxies contributing to a single IR or UV flux. However, if multiple SWIRE or GALEX counterparts are found to lie near an Hα source, the closest one is used. For Hα sources having Hα neighbors within 3′ (seven sources), there are three UV sources which appear as extended (blended) sources, which account for <2% of the entire sample. The sample is further reduced in size by requiring sources to have data in both UV bands as well as the 24 μm band. Both the WySH + SWIRE and WySH + SWIRE + GALEX catalogs are used in this research where appropriate. Ultimately, this can be considered a 24 μm selection. The sample sizes are listed in Table 1.

2.3. Corrections

2.3.1. k Corrections

For k corrections, the central redshift value for each epoch is used rather than the redshift for each source within a given epoch since $\delta_z$ per epoch is ~0.02 and the redshifts for this sample have been determined photometrically (Rowan-Robinson et al. 2008). The UV data for the sample were k corrected by calculating the slope between the observed FUV and NUV fluxes and by extrapolating from that slope to the rest-frame FUV and NUV fluxes. The FUV k corrections are modest and have median values of $f_{k}(FUV)_{true}/f_{k}(FUV)_{obs} = [0.91, 0.89, 0.86, 0.85]$ at $z \sim [0.16, 0.24, 0.32, 0.40]$. Comparing this to local data from the Spitzer Local Volume Legacy (LVL) Survey (Kennicutt et al. 2008; Dale et al. 2009b; J. C. Lee et al. 2010, in preparation; for Hα, 24 μm, and UV data, respectively), and the Nearby Galaxy Survey (NGS; Gil de Paz et al. 2007) in Figure 3, the UV continuum of late-type galaxies ($T \geq 3$) is also relatively flat with median values along the y-axis of 0.06 dex for the Spitzer LVL Survey and 0.02 dex for the NGS, with respect to log$(vL_v (NUV))$. Rest-frame data from WySH are also shown. Triangles represent data at $z \sim 0.16$, squares represent data at $z \sim 0.24$, crosses represent data at $z \sim 0.32$, and diamonds represent data at $z \sim 0.40$.

![Figure 3](http://www.galex.caltech.edu/survey/fig3.png)

**Figure 3.** Ratio of log$(vF_{nuv}/vF_{NUV})$ vs. log$(vL_v (NUV))$. Small pluses represent data from late-type ($T \geq 3$) galaxies in the Spitzer LVL Survey and the NGS, while small diamonds represent early-type ($T < 3$) galaxies in the Spitzer LVL Survey and the NGS. These local data show that log$(vF_{nuv}/vF_{NUV})$ remains relatively flat with median values (for the late-type galaxies) of 0.06 dex for the Spitzer LVL Survey and 0.02 dex for the NGS, with respect to log$(vL_v (NUV))$. (A color version of this figure is available in the online journal.)

2.3.2. AGN Corrections

The empirical method of Lacy et al. (2004) is used to identify possible AGNs within our sample (see Figure 4). The different “sequences” identified in Lacy et al. (2004) are not immediately apparent in Figure 4 since the large Sloan Digital Sky Survey.
(SDSS) data set is also not included here as in Figure 1 of Lacy et al. (2004). Lacy et al. (2004) describe one “sequence” to have blue colors in $L_\alpha/(5.8\,\mu m)/L_\nu(3.6\,\mu m)$ and very red colors in $L_\nu(8.0\,\mu m)/L_\nu(4.5\,\mu m)$, which they describe as likely to be low-redshift ($z \lesssim 0.2$) galaxies whose PAH emission bands have not been significantly redshifted out of the 8.0 $\mu m$ filter. Within this same sequence but at higher redshifts, the 7.7 $\mu m$ PAH feature is no longer observed with the 8.0 $\mu m$ filter, which would give those sources a bluer color in $L_\nu(8.0\,\mu m)/L_\nu(4.5\,\mu m)$, and a redder color in $L_\nu(5.8\,\mu m)/L_\nu(3.6\,\mu m)$ since the 3.3 $\mu m$ PAH feature will have redshifted out of the 3.6 $\mu m$ band. In Figure 4, it is clear that most of the sources in this sequence as defined by Lacy et al. (2004) are found at either $z \sim 0.16$ or $z \sim 0.24$, however, the sources at $z \sim 0.32$ and $z \sim 0.40$ start to span the gap between the two sequences due to the effects of redshift and lie closer to, or within, the enclosed region. The other “sequence” that Lacy et al. (2004) describe has red colors in both filter pairs; this is where they find SDSS- and radio-selected quasars. The dashed lines in Figure 4 enclose this region, as defined empirically by Lacy et al. (2004). Regarding the WySH sample, the Lacy et al. (2004) empirical classification of AGNs is used to conservatively identify the three rightmost sources within the box in Figure 4 as AGNs. These three sources are removed from the remainder of this study. The identities are less clear for the other sources near the AGNs/star-forming boundaries, which are indicated by dashed lines. It is possible that some of these sources are composite sources (i.e., a combination of AGN and star formation within the galaxy). Other sources, particularly at $z \sim 0.32$ and $z \sim 0.40$, may have simply been redshifted into this region based on the previous description of the “sequences.” Without spectra, it is impossible to confirm whether or not the sources in question are AGN, star forming, or a composite, and these sources near the AGN/SF boundaries are not removed from the sample.

3. RESULTS

3.1. Dust Attenuation via 24 $\mu m$ and FUV

Very few sources in this study have detections of far-IR emission, so the traditional $L_{\text{TIR}}/L_{\nu}(\text{FUV})$ tracer of the attenuation by dust cannot be used, and is replaced here with $\nu L_\nu(24\,\mu m)/\nu L_\nu(\text{FUV})$ as proxy. The rest-frame 24 $\mu m$ emission is approximately 10% of the TIR emission on average for normal star-forming galaxies, but the dispersion is large. For normal star-forming galaxies at the epochs studied here, the full range in 24 $\mu m$/TIR spans a factor of 2 (Dale et al. 2005, see Figure 16). Figure 5 shows the dust attenuation diagnostic, $\nu L_\nu(24\,\mu m)/\nu L_\nu(\text{FUV})$, as a function of the H$\alpha+24\,\mu m$ SFR from Kennicutt et al. (2009):

$$SFR(M_\odot \text{yr}^{-1}) = 7.9 \times 10^{-42}[(aL(\text{H}\alpha_{\text{obs}}) + bL_\nu(24\,\mu m))]$$

where both luminosities are in erg s$^{-1}$, and $L_\nu(24\,\mu m)$ is expressed as $\nu L_\nu$. The best fit to the data from Kennicutt et al. (2009) gives $b/a = 0.020$, which is based on the integrated fluxes of a large sample of galaxies. Figure 5 follows the trend that galaxies with larger SFRs tend to be more dusty, as inferred from the 24 $\mu m$/FUV ratio (Hopkins et al. 2001a). Looking at only the SFR portrayed along the $x$-axis, a trend toward higher SFRs at higher redshifts is seen, which has been shown by a number of other studies (e.g., Cowie et al. 2004; Le Floc’h et al. 2005; Doherty et al. 2006; Dale et al. 2008; Prescott et al. 2009). This evolution could partially be due to sample selection whereby only the brighter galaxy subsets are observed at higher redshifts. The data from all four epochs appear to have roughly the same average attenuation by dust, as indicated by the large symbols in Figure 5 (and the information portrayed in Figure 7). This result agrees with the recent results of Buat et al. (2009). While the ensemble average is relatively constant from epoch to epoch, each epoch separately exhibits a larger attenuation by dust for higher SFRs. Hence, given that the average galaxy SFR increases with the look-back time, an epoch-to-epoch comparison at a fixed SFR suggests a mild decrease in dust attenuation with redshift. The argument of a decrease in the amount of attenuation by dust with the look-back time is consistent with results from Buat et al. (2007a) and combined results from Reddy et al. (2006), Buat et al. (2007b), and Burgarella et al. (2007), who have found dust attenuation values decrease from $z \sim 0$ to $z \sim 2$, as discussed previously.

3.2. Dust Attenuation via H$\alpha$ and 24 $\mu m$

The empirical argument for a decrease in dust attenuation is perhaps more readily apparent from the data portrayed in Figure 6. Figure 6 shows the dust attenuation diagnostic,
Recent diagnostic of dust attenuation, $[aL(H\alpha_{obs}) + bL_\nu(24\mu m)]/L(H\alpha_{obs})$, where the numerator is taken from Kennicutt et al. (2009) as a function of the $H\alpha + 24\mu m$ SFR from Kennicutt et al. (2009), and $b/\alpha = 0.020$. $A_{\alpha}$ (Kennicutt et al. 2007) is plotted on the right-hand axis. Symbols are the same as in Figure 5. (A color version of this figure is available in the online journal.)

$$[aL(H\alpha_{obs}) + bL_\nu(24\mu m)]/L(H\alpha_{obs})$$

versus the SFR indicator of Kennicutt et al. (2009, Equation (2)). Here, again, the expected trend that galaxies with higher SFRs tend to be more dusty can be seen (Hopkins et al. 2001a), although, in this case the trend is seen most strongly for a given redshift rather than for the entire data set. The right-hand axis translates this diagnostic into a value of magnitudes of $A_{\alpha}$ extinction (Kennicutt et al. 2007). The large symbols in Figure 6 represent the average values for each epoch. As in Figure 5, the average dust attenuation remains relatively constant from epoch to epoch. Moreover, it is likewise more illuminating to compare the attenuation from epoch to epoch at a fixed SFR. For a given SFR, the typical amount of attenuation by dust decreases with increasing redshift, echoing the combined results of Reddy et al. (2006), Buat et al. (2007b), and Burgarella et al. (2007). While these studies use a UV selection, no comparable studies exist using an $H\alpha$ selection. For work based on other selections, see, for example, Buat et al. (2007a), Xu et al. (2007), and Zheng et al. (2007). These comparisons do not change the result that while the ensemble average of dust attenuation does not change as a function of the redshifts sampled here, we expect higher redshift galaxies to show higher values of attenuation since they are typically exhibiting larger SFRs. However, we find that higher redshift galaxies show lower values of attenuation at a given luminosity (i.e., star formation rate).

### 3.3. Comparison of Dust Attenuation Diagnostics

To compare Figures 5 and 6, the correlation coefficients for each diagnostic were computed. The log($vL_\nu(24\mu m)/vL_\nu(FUV)$) diagnostic gives $r = 0.545$ and the log($[aL(H\alpha_{obs}) + bL_\nu(24\mu m)]/L(H\alpha_{obs})$) diagnostic gives $r = 0.452$. To investigate the statistical significance of the two diagnostics, the program R10 (R Development Core Team 2009) was used to analyze the data with a linear model. Based on the multiple $R^2$ statistic, $\sim 0.11\%$ of the variability in log($vL_\nu(24\mu m)/vL_\nu(FUV)$) can be explained by the SFR, and $\sim 0.01\%$ of the variability in log($[aL(H\alpha_{obs}) + bL_\nu(24\mu m)]/L(H\alpha_{obs})$) can be explained by a linear association with log(SFR). It can be argued that the latter diagnostic is slightly more correlated with SFR because the $[aL(H\alpha_{obs}) + bL_\nu(24\mu m)]$ parameter appears on both axes, however, based on the statistical analysis described above, this positive correlation is not seen in the data.

The dust attenuation seems to be higher when looking at the line emission from $H\alpha$ (Figure 6) versus the UV continuum (Figure 5). However, it is more informative to look at the amount of attenuation by dust determined from both diagnostics on the same scale ($A_{V_{cont}}$ (continuum) in magnitudes) with respect to redshift (see Figure 7). In order to convert $vL_\nu(24\mu m)/vL_\nu(FUV)$ to $A_{V_{cont}}$, $vL_\nu(24\mu m)$ was multiplied by 10 to approximate TIR (Dale et al. 2005, Figure 16). (This is a large source of uncertainty, approximately a factor of 2.) The following prescription from Buat et al. (2007a) was used to determine $A_{V_{cont}}$ (in magnitudes) from TIR/FUV:

$$A(FUV) = -0.0333 \left( \log \frac{L_{TIR}}{L_{FUV}} \right)^3 + 0.3522 \left( \log \frac{L_{TIR}}{L_{FUV}} \right)^2 + 1.1960 \log \frac{L_{TIR}}{L_{FUV}} + 0.4967,$$

$$A(FUV) = 2.678A_{V_{cont}}.$$  

The reddening curve from Li & Draine (2001) converts from $A_{H\alpha}$ to $A_{V_{cont}}$ (emission line) for the $[aL(H\alpha_{obs}) + bL_\nu(24\mu m)]/L(H\alpha_{obs})$ diagnostic. The value $R_V' = 4.05$ is used to convert from $A_{V_{cont}}$ to $A_{V_{cont}}$, $A_{V_{cont}} \sim 1.8A_{V_{cont}}$ (Calzetti et al. 2000; Calzetti 2001). As can be seen in Figure 7, when the two diagnostics are placed on the same $A_{V_{cont}}$ scale, they agree within the errors. This consistency holds whether the errors are determined through population statistics or formal measurement uncertainties. Both diagnostics show no noticeable evolution in the amount of dust attenuation as a function of redshift.

There are additional challenges to comparing $vL_\nu(24\mu m)/vL_\nu(FUV)$ and $[aL(H\alpha_{obs}) + bL_\nu(24\mu m)]/L(H\alpha_{obs})$. The $H\alpha$ and the IR continuum emission both trace star formation on timescales of $\lesssim 10^7$ yr, while the UV continuum traces SFRs on timescales of $\sim 10^8$ yr (e.g., Kennicutt 1998; Meynet & Maeder 2000; Iglesias-Páramo et al. 2004). Thus, the $[aL(H\alpha_{obs}) + bL_\nu(24\mu m)]/L(H\alpha_{obs})$ is naturally a “cleaner” diagnostic of attenuation by dust since all factors involved arise from similar regions, which are physically separated from each other.
much of the UV emission, as well as similar timescales (for a counterargument, see Gordon et al. 2000; Buat et al. 2005; Cortese & Hughes 2009). An additional challenge to interpreting global \( \nu L_\nu (24 \mu \text{m})/\nu L_\nu (FUV) \) measures lies in the average dust temperature of a galaxy. The 24 \( \mu \text{m} \) emission is not only sensitive to the amount of dust, which directly leads to attenuation, but it is also sensitive to the temperature of the dust. In the dust models of Draine & Li (2007), the flux at 24 \( \mu \text{m} \) largely represents emission from very small grains with effective radii of 15–40 Å. These intermediate-sized dust grains are responsible for a widely varying portion of the bolometric IR luminosity depending on the intensity of the interstellar radiation field. As the intensity of the radiation field increases linearly, the 24 \( \mu \text{m} \) emission from the dust grains will increase more rapidly, appearing overluminous with respect to the linear increase of the radiation field (see Calzetti et al. 2007). Naturally, any monochromatic indicator of the dust emission is limited in its ability to effectively encapsulate the emission processes of all dust grains that emit between 1 and 1000 \( \mu \text{m} \), and the 24 \( \mu \text{m} \) bandpass is no exception.

3.4. Comparison with Dust Attenuation Results at \( z \sim 0 \)

It is also important to compare the WySH data set to a data set at \( z \sim 0 \), in order to increase the redshift baseline to see how the amount of attenuation by dust evolves from \( z \sim 0 \) to \( z \sim 0.40 \). Using the same diagnostics as in Figures 5 and 6, data from the Spitzer LVL Survey and SINGS are added to Figures 8 and 9 (Kennicutt et al. 2008; Dale et al. 2009b; J. C. Lee et al. 2009, in preparation; for H\( \alpha \), 24 \( \mu \text{m} \), and UV data, respectively). These samples were chosen because of their multi-wavelength data sets that somewhat mirror the data already being used in this study. In particular, the Spitzer LVL Survey also contains a larger number of low-luminosity galaxies than would be detected at the redshifts of WySH (Dale et al. 2009b). It is clear from Figures 8 and 9 that the local population of galaxies provides a natural extension to lower SFRs and lower levels of dust attenuation. Unfortunately, where the WySH and local populations overlap in SFR, there are not enough data to infer any meaningful conclusions. The emphasis of this comparison is on the fact that the dust attenuation does, in fact, increase with SFR.

4. SUMMARY

The study of the evolution of dust attenuation within galaxies over cosmic time has led to a set of divergent results. Indeed, the attenuation by dust has been found to decrease from \( z \sim 0 \) to \( z \sim 0.2 \) in Buat et al. (2007a) and Reddy et al. (2006), Buat et al. (2007b), and Burgarella et al. (2007) (combined) to increase from \( z \sim 0 \) to \( z \sim 1 \) (Le Floc’h et al. 2005; Schiminovich et al. 2005; Takeuchi et al. 2005) and to remain essentially unchanged from \( z \sim 0.6 \) to 0.8 to the present epoch (Bell et al. 2005; Choi et al. 2006; Xu et al. 2007; Zheng et al. 2007). These disparate results could be the effect of different sample selection criteria, with one study focusing on UV-bright galaxies, another on ULIRGS, etc. The selection criteria for the various studies are summarized in Table 2. There does not appear to be any one single selection criteria that maps to any of the three above-mentioned categories of results (dust attenuation increases with \( z \), decreases with \( z \), or remains unchanged), so it is difficult to determine whether or not (or to what extent) the selection criteria drive the conclusions made in the previous efforts.

In an effort to decipher this problem, we present multi-wavelength results that explore the evolution of the amount of dust attenuation from \( z \sim 0.16 \) to \( z \sim 0.40 \). We use H\( \alpha \) data from WySH for a uniform initial source selection, and further constrain our sample by selecting according to detections available in IR data from SWIRE and UV data from GALEX. Using a traditional measure of dust attenuation, \( \nu L_\nu (24 \mu \text{m})/\nu L_\nu (FUV) \), we show that over this range in redshift, there is no noticeable evolution in the ensemble average amount of attenuation by dust of our sources. Looking over this same range in redshift, with a more recent measure of dust attenuation, \([a L(\text{H}\alpha_{\text{obs}})+b L_\nu (24 \mu \text{m})]/L(\text{H}\alpha_{\text{obs}})\), we also show that there is no noticeable evolution in the ensemble average amount of attenuation by dust. However, looking epoch by epoch for a given SFR, a mild decrease in dust attenuation with the look-back time can be seen. Adding data from a couple of local galaxy samples, spanning both a volume-complete sample (Spitzer LVL Survey) and one that is more geared toward IR-bright galaxies (SINGS) shows no (or very little) evolution in dust attenuation in galaxies from \( z \sim 0 \) to \( z \sim 0.40 \). Two general trends found in the data are that the dust attenuation increases with SFR and that galaxies were probably intrinsically more luminous at times in the past.

Future efforts will incorporate H\( \alpha \) data at \( z \sim 0.8 \) and 2.2 from the NEWFIRM Narrowband H\( \alpha \) Survey. We also plan to extract our own flux measurements from the GALEX data. The NEWFIRM Narrowband H\( \alpha \) Survey Collaboration is also obtaining spectral data for the H\( \alpha \) sources that are identified at \( z \sim 0.8 \) and 2.2 in order to measure the dust attenuation.
Table 2
Summary of Previous Studies of Dust Attenuation as a Function of Increasing Redshift

| Method | Dust Attenuation Amplitude | Source Selection | Reference |
|--------|-----------------------------|------------------|-----------|
| LD     | \( (A_{\text{FUV}}) \sim 3 \text{ mag and decreases from } z = 0 \text{ to } z = 0.7 \) | \( 24 \mu\text{m selection (} z \lesssim 1 \); LIRGs only \) | Buat et al. (2007a) |
| LF     | \( A_{\text{FUV}} \text{ decreases from } \sim 3.4 \text{ to 1.7 mag from } z = 0 \text{ to } z = z^* \) | separate FUV & FIR selections (\( z \sim 0 \)) | Buat et al. (2007b) |
| LF     | \( A_{\text{FUV}} \text{ decreases from } \sim 3.4 \text{ to 1.7 mag from } z = 0 \text{ to } z = z^* \) | UV selection of Lyman break galaxies (\( z \sim 1 \)) | Burgarella et al. (2007) |
| LF     | \( A_{\text{FUV}} \text{ decreases from } \sim 3.4 \text{ to 1.7 mag from } z = 0 \text{ to } z = z^* \) | BM/BX (optical) criteria similar to Lyman break galaxies at \( z \sim 3 \) (\( z \sim 2 \)) | Reddy et al. (2006) |
| Ind    | \( A_{\text{FUV}} \text{ decreases } \sim 1.5 \text{ mag from } z \sim 0.16 \text{ to } z \sim 0.40 \) | \( 24 \mu\text{m selection with } \text{H} \alpha \text{ and UV detections required} \) | This study |

Dust attenuation increases

| Method | Dust Attenuation Amplitude | Source Selection | Reference |
|--------|-----------------------------|------------------|-----------|
| LF     | Comoving IR energy density \( (1 + z)^{7.9 \pm 0.4} (0 \lesssim z \lesssim 1) \) | \( 24 \mu\text{m selection (} z \lesssim 1 \)) | Le Floc’h et al. (2005) |
| LD     | \( \rho_{1500} = (1 + z)^{5.6 \pm 0.7} \text{ to } z \sim 1 \) | UV selection (\( z \lesssim 3 \)) | Schiminovich et al. (2005) |
| LD     | \( \rho_{\text{FUV}}/\rho_{\text{FUV}} \text{ increases from } \sim 4 \text{ to } \sim 15 \text{ (} z = 0 \text{ to } z \sim 1 \) | FUV and IR luminosity functions from previous works | Takeuchi et al. (2005) |

Dust attenuation same as at \( z \sim 0 \)

| Method | Dust Attenuation Amplitude | Source Selection | Reference |
|--------|-----------------------------|------------------|-----------|
| Ind    | ...                         | NIR + MIR selection (\( z \sim 0.8 \)) | Choi et al. (2006) |
| LD     | ...                         | \( 24 \mu\text{m selection (} z \sim 0.7 \)) | Bell et al. (2005) |
| Ind    | ...                         | Separate NUV and \( 24 \mu\text{m selections of LIRGs and ULIRGS (} z \sim 0.6 \)) | Xu et al. (2007) |
| LD     | ...                         | COMBO-17 photo-\( c \) (\( 0.6 \lesssim z \lesssim 0.8 \)) | Zheng et al. (2007) |

Notes.

- Results are derived from either a luminosity function (LF), a luminosity density (LD), or a collection of individual galaxies (Ind).
- Amplitude of dust attenuation evolution and what range the evolution is measured over.
- The results from Buat et al. (2007b), Burgarella et al. (2007), and Reddy et al. (2006) are combined to determine the results presented in Burgarella et al. (2007) out to \( z \sim 2 \).

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