THE ORIGIN OF THE 4.5 μm EXCESS FROM DWARF GALAXIES

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Received 2008 December 9; accepted 2009 April 25; published 2009 May 27

ABSTRACT

Dwarf galaxies tend to have redder [3.6 μm] − [4.5 μm] Spitzer broadband colors than spirals. To investigate this effect, for a large sample of dwarf galaxies we combine Spitzer fluxes with data at other wavelengths and compare to population synthesis models. Lower metallicity systems are found to have redder [3.6] − [4.5] colors on average, but with considerable scatter. The observed range in [3.6] − [4.5] color is too large to be accounted for solely by variations in stellar colors due to age or metallicity differences; interstellar effects must contribute as well. For the reddest systems, the 4.5 μm luminosity may not be a good tracer of stellar mass. We identify three factors that redden this color in dwarfs. First, in some systems, strong Brγ emission contributes significantly to the 4.5 μm emission. Second, in some cases high optical depths lead to strong reddening of the starlight in the Spitzer bands. Third, in some galaxies, the nebular continuum dominates the 4.5 μm flux, and in extreme cases, the 3.6 μm flux as well. The harder UV radiation fields in lower metallicity systems produce both more gaseous continuum in the infrared and more Brγ per star formation rate. The combination of these three factors can account for the 4.5 μm excess in our sample galaxies, thus it is not necessary to invoke a major contribution from hot dust to the 4.5 μm band. However, given the uncertainties, we are not able to completely rule out hot dust emission at 4.5 μm. More spectroscopic observations in the 3–5 μm range are needed to disentangle these effects.

Key words: galaxies: dwarf – galaxies: general – galaxies: individual (SBSG 033–052, HS 0822+3542, II Zw 40, I Zw 18)

1. INTRODUCTION

The mid-infrared spectra of low-metallicity dwarf galaxies are well known to differ from those of spirals, with weaker polycyclic aromatic hydrocarbon (PAH) emission features and higher [Ne iii]/[Ne ii] ratios (Thuan et al. 1999; Madden 2000; Galliano et al. 2003; Houck et al. 2004; Hunt et al. 2005; Madden et al. 2006; Wu et al. 2006). This may be due to harder interstellar radiation fields (ISRFs) in dwarfs because of lower dust extinction, leading to PAH destruction (Galliano et al. 2003, 2005; Madden et al. 2006), or to delayed creation of carbon dust by asymptotic giant branch (AGB) stars in dwarfs (Galliano et al. 2008). These differences are reflected in the mid-infrared broadband colors of dwarfs, which show depressed 8 μm emission relative to 24 μm, compared to spirals (Boselli et al. 1998; Engelbracht et al. 2005; Rosenberg et al. 2006, 2008). This is interpreted as a weakening of the 7.7 μm PAH feature in dwarfs. Dwarf and spiral spectral energy distributions also differ at longer wavelengths; spiral spectra peak in the far-infrared, while dwarf spectra peak at shorter wavelengths, ≳25–60 μm (Galliano et al. 2003; Houck et al. 2004; Hunt et al. 2005). This implies warmer large dust grains in dwarf galaxies on average. Low-metallicity galaxies also tend to have lower total dust-to-gas mass ratios than higher metallicity systems (e.g., Engelbracht et al. 2008; Hirashita et al. 2008).

The Spitzer [3.6] − [4.5] broadband colors of irregular/Sm galaxies also differ from those of spirals, being redder on average (Pahre et al. 2004; Engelbracht et al. 2005; Smith et al. 2007). This color difference, however, has proven more difficult to interpret. Since the 3–5 μm radiation from galaxies may be a combination of starlight and interstellar emission, it can be difficult to accurately disentangle the contributions from these components to the observed broadband fluxes. Pahre et al. (2004) suggested that this reddening is due to younger stars in Irr/Sm galaxies compared to spirals, with hotter stars having redder [3.6] − [4.5] colors. In general, hotter stars tend to have redder L/M colors (~[3.6] − [4.5]) than cooler stars (Cox 2000). Alternatively, these color differences have been attributed to hot dust in dwarf galaxies contributing at 4.5 μm (Engelbracht et al. 2005; Hunter et al. 2006). The Brγ line may also contribute significantly to the 4.5 μm band (Churchwell et al. 2004; Elmegreen et al. 2006). In addition, the nebular continuum in the infrared can also contribute significantly at wavelengths ≥3 μm in low-metallicity systems (e.g., Krüger et al. 1995). Another factor may be the 3.3 μm PAH feature, which contributes to the 3.6 μm Spitzer band. A lower heavy element abundance, and therefore less PAHs, can redden the [3.6] − [4.5] color. Also, stars with low metal abundances may have redder colors because of less line blanketing in the 4.5 μm band (M. Cohen 2006, private communication). Evolved stars can also redden this color, for example, Miras are 1–2 mag redder in L/M than non-variable optically bright stars (Smith 2003). In highly obscured systems, reddening due to dust extinction can also be important even in the Spitzer bands (e.g., Roussel et al. 2006).

To determine the origin of the red [3.6] − [4.5] colors in dwarf galaxies, for a large sample of dwarfs we have collected Spitzer mid-infrared fluxes, metallicities, and ground-based optical, near-infrared, and radio measurements from the literature. Combining these data with population synthesis modeling, we have investigated trends in the stellar and interstellar spectra with metallicity and age. In Section 2 of this paper, we describe the sample and the data. In Section 3, we compare the [3.6] − [4.5] colors with other properties of the galaxies. We discuss expected [3.6] − [4.5] colors from starlight in Section 4, and in Section 5, we investigate Brγ contributions to the 4.5 μm band. In Section 6, we discuss reddening due to dust extinction in the Spitzer bands. In Section 7, we discuss reddening of the

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[3.6] − [4.5] color due to the nebular continuum. In Section 8, non-stellar contributions to the 3.6 μm Spitzer band are investigated. In Section 9, the question of hot dust contributions at 4.5 μm is discussed. Morphology is discussed in Section 10, while luminosity and stellar mass are investigated in Section 11. Some additional issues are discussed in Section 12, and conclusions are presented in Section 13.

2. THE SAMPLE AND THE DATA

To investigate how the [3.6] − [4.5] color depends upon metallicity and other properties of dwarf galaxies, we collected Spitzer 3.6, 4.5, 5.8, 8.0, and 24 μm fluxes from the literature for a sample of 71 irregular, blue compact dwarf (BCD), Sm, Sd, and other dwarf galaxies, for which oxygen abundances are available. This sample is not complete in any sense, however, it spans a large range of metallicity, absolute magnitude, Spitzer luminosities, and gas content. Table 1 lists the references from which we extracted the data used in this study.

For all of the galaxies in our sample with very red or very blue [3.6] − [4.5] published colors, we downloaded the Spitzer archival images and checked the published values. For all except the bluest galaxy in the sample, UGC 4483, the colors we obtained agreed with the published colors within ∼0.15 mag. For UGC 4483, however, our [3.6] − [4.5] color is −0.16, compared to −0.39 from Engelbracht et al. (2008). For this galaxy, we used our fluxes rather than the published numbers.

Table 1

| Type of Data                  | Number Available | References                                                                 |
|------------------------------|------------------|---------------------------------------------------------------------------|
| Spitzer 3.6, 4.5, 5.8, 8.0, and 24 μm fluxes | 71               | Rosenberg et al. (2006), Rosenberg et al. (2008), Dale et al. (2007)       |
|                              |                  | Corbin et al. (2008), Engelbracht et al. (2008)                           |
| Oxygen abundances            | 71               | Skillman et al. (1989), Lequeux et al. (1979)                              |
|                              |                  | Masegosa et al. (1994), Miller & Hodge (1996)                             |
|                              |                  | van Zee et al. (1997), Lee & Skillman (2004)                              |
|                              |                  | Mendes de Oliveira et al. (2006), Sidoli et al. (2006)                    |
|                              |                  | Rosenberg et al. (2006), Corbin et al. (2008)                             |
|                              |                  | Engelbracht et al. (2008)                                                 |
| 21 cm H I fluxes             | 40               | Begum et al. (2006), Chengalur et al. (2006), Paturel et al. (2003)       |
|                              |                  | Hutchmeier et al. (2005), Pustilnik & Martin (2007)                       |
| He fluxes                    | 49               | Hunter & Gallagher (1985); Hunter et al. (1994)                           |
|                              |                  | Lehner & Heckman (1995), Armus et al. (1990)                              |
|                              |                  | Gallagher et al. (1991), Miller & Hodge (1994)                           |
|                              |                  | Marlowe et al. (1995), Méndez et al. (1999)                               |
|                              |                  | Gil de Paz et al. (2003), James et al. (2004)                             |
|                              |                  | Pustilnik et al. (2004), Hunter & Elmegreen (2004)                        |
|                              |                  | Begum et al. (2006), Schmitt et al. (2006)                                |
|                              |                  | Rosenberg et al. (2006), Rosenberg et al. (2008), Engelbracht et al. (2008) |
| He/Hz ratios                 | 53               | French (1980), Kinman & Davidson (1981)                                  |
|                              |                  | Campbell et al. (1986)                                                   |
|                              |                  | de Grijs et al. (1992), Kennicutt (1992)                                  |
|                              |                  | Vaccarino & Conti (1992), Rönnback & Bergvall (1995)                     |
|                              |                  | Miller & Hodge (1996), Izotov et al. (1997), van Zee (2000)               |
|                              |                  | Kong et al. (2002), Guseva et al. (2000)                                  |
|                              |                  | Kniazev et al. (2003), Kniazev et al. (2004), Rosenberg et al. (2006)    |
|                              |                  | Moustakas & Kennicutt (2006), Izotov et al. (2007)                        |
| Brα and/or Brγ fluxes        | 3                | Moorwood & Oliva (1988), Kawara et al. (1989)                             |
|                              |                  | Dale et al. (2001), Verma et al. (2003)                                   |
| Hβ equivalent widths         | 54               | Campbell et al. (1986), Bergvall & Olofsson (1986)                       |
|                              |                  | Terlevich et al. (1991), Kennicutt (1992), Vaccarino & Conti (1992)     |
|                              |                  | Rönnback & Bergvall (1995), Pustilnik et al. (1999)                      |
|                              |                  | Guseva et al. (2000), van Zee (2000), Kong et al. (2002)                 |
|                              |                  | Kniazev et al. (2004), Salzer et al. (2005), Thuan & Izotov (2005)       |
|                              |                  | Izotov et al. (2006), Moustakas & Kennicutt (2006)                       |
|                              |                  | Izotov et al. (2007)                                                     |
| 9.7 μm silicate absorption   | 4                | Aitken et al. (1982), Phillips et al. (1984)                             |
|                              |                  | Thuan et al. (1999), Houck et al. (2004), Brandl et al. (2006)           |
| UBVRI magnitudes             | 55               | Salzer et al. (1989), Rönnback & Bergvall (1994)                         |
|                              |                  | (≥3 bands) Makarova et al. (1998), Makarova (1999)                       |
|                              |                  | Méndez & Esteban (1999), Cairós et al. (2001), Bergvall & Östlin (2002) |
|                              |                  | Paturel et al. (2003), Gil de Paz et al. (2003)                         |
|                              |                  | Jangren et al. (2005), Noeske et al. (2005)                              |
|                              |                  | Pustilnik et al. (2004), Moustakas & Kennicutt (2006)                    |
|                              |                  | Hunter & Elmegreen (2006)                                                |
| JHK magnitudes               | 55               | Spinoglio et al. (1995), Vanzi et al. (2000), Jarrett et al. (2003)      |
|                              |                  | (≥1 band) Vaduvescu et al. (2005), Rosenberg et al. (2006)               |
|                              |                  | Moustakas & Kennicutt (2006), Dale et al. (2007)                         |
|                              |                  | Engelbracht et al. (2008)                                                |
Figure 1. Left: a plot of log(O/H) + 12 vs. [3.6] − [4.5] for the sample dwarf galaxies. The different colors represent different H\textsc{i} mass to stellar mass ratios, as indicated by the H\textsc{i} magnitude m(H\textsc{i}) minus the 3.6 \textmu m magnitude [3.6]. The H\textsc{i} magnitude is defined as in Paturel et al. (2003). The magenta open diamonds are the most H\textsc{i}-rich systems, with mag(H\textsc{i}) − [3.6] < 1.3. The red filled circles have 1.3 < mag(H\textsc{i}) − [3.6] ≤ 3.0, the green crosses 3.0 < mag(H\textsc{i}) − [3.6] ≤ 4.1, the cyan filled squares 4.1 < mag(H\textsc{i}) − [3.6] ≤ 5.5, and the blue asterisks 5.5 < mag(H\textsc{i}) − [3.6]. Galaxies marked in the black open squares do not have H\textsc{i} data available. Typical uncertainties on the Spitzer [3.6] − [4.5] colors of galaxies are ~0.05 (Smith et al. 2007). Some of the galaxies are labeled. Right: a similar plot for the comparison sample of “normal” spiral galaxies.

We also collected total-galaxy 21 cm H\textsc{i} and H\textsc{z} fluxes for the sample galaxies. We also used H\textsc{z}/H\textbeta ratios from the literature, preferably global (total-galaxy) values when possible; otherwise, we used smaller aperture measurements. In addition, we searched for both total-galaxy and smaller aperture Br\textalpha and Br\gamma measurements. We also obtained H\beta equivalent widths and measurements of the 9.7 \textmu m silicate absorption feature optical depth for our sample galaxies, preferring global values over small-aperture measurements when available. In Table 1, for each type of data, we give the number of galaxies with such data available.

We also obtained total-galaxy optical UBVRI and near-infrared JHK broadband fluxes for our sample from the literature. These magnitudes were corrected for Galactic extinction, when necessary, and converted to Jy using the zero points in Bessell et al. (1998). In a number of cases, large discrepancies were found between different published magnitudes for the same galaxy. In these cases, we did not use either measurement in our analysis.

As a comparison sample of spiral galaxies, we started with the sample of nearby “normal” (not strongly interacting) spirals discussed in Smith et al. (2007). These galaxies have total-galaxy Spitzer infrared and ground-based optical and near-infrared broadband fluxes available from Dale et al. (2007). Most have total H\textalpha fluxes available from Kennicutt et al. (2003), and Pa\alpha/H\textalpha ratios for the inner 50′′ available from Calzetti et al. (2007). As spirals tend to have radial abundance gradients, for comparison to the dwarfs we selected spirals which have disk-averaged oxygen abundances available (Moustakas & Kennicutt 2006; Calzetti et al. 2007). After removing Sd galaxies, there are 13 galaxies in the spiral sample.

3. [3.6] − [4.5] COLORS AS A FUNCTION OF METALLICITY, GAS CONTENT, AND STAR FORMATION RATE

In the left panel of Figure 1, we compare the [3.6] − [4.5] color against oxygen abundance for our sample dwarf galaxies.

The right panel shows the same plot for the spirals. The dwarfs are on average redder in [3.6] − [4.5], in addition to having lower metallicities. For the dwarfs, a relation is seen, in that colors redder than [3.6] − [4.5] > 0.3 are only seen at low abundances, log(O/H) + 12 ≤ 8.2 (~1/3 solar). In contrast, the spirals all have [3.6] − [4.5] ~ 0.0, and disk-averaged log(O/H) + 12 > 8.2.

For the dwarfs, there is considerable scatter in Figure 1. To test whether this scatter is due solely to differing amounts of interstellar matter, with more gas-rich galaxies having a larger amount of dust and therefore more 4.5 \textmu m excess, in Figure 1 we color coded the data points according to their m(H\textsc{i}) − [3.6] color, where m(H\textsc{i}) is the magnitude in the 21 cm H\textsc{i} line (de Vaucouleurs et al. 1991; Paturel et al. 2003). The corresponding H\textsc{i} mass for the dwarfs range from 7 × 10^6 M\odot to 7 × 10^9 M\odot. In this plot, as log(O/H) increases, m(H\textsc{i}) − [3.6] tends to increase (i.e., the H\textsc{i} mass to 3.6 \textmu m luminosity ratio M_{H\textsc{i}}/ L_{3.6} decreases). This is consistent with results of previous studies (e.g., Fisher & Tully 1975), which show that lower metallicity systems tend to be richer in H\textsc{i} relative to their stellar mass. However, for a given metallicity, no strong trend of m(H\textsc{i}) − [3.6] with [3.6] − [4.5] is found. Thus, the 4.5 \textmu m excess does not appear to be due to an increasing mass fraction of interstellar matter. This result is uncertain, however, because molecular gas is not included in this plot. Many of these galaxies are undetected in CO, the standard tracer of molecular gas in galaxies, and the amount of molecular gas present is uncertain.

In Figure 2, we compare the [3.6] − [4.5] colors of these galaxies with the [3.6] − [24] colors. The left panel shows the dwarfs, the right the spirals. In this figure, we have color coded the data points as a function of oxygen abundance. The 24 \textmu m luminosity is considered a good tracer of star formation rate, as it arises from small dust grains heated by UV photons (e.g., Calzetti et al. 2005). If the 3.6 \textmu m flux is mainly due to older stars, then [3.6] − [24] is roughly a measure of the mass-normalized star formation rate, and therefore the intensity of the UV field. Figure 2 shows that indeed more intense UV fields are correlated with more 4.5 \textmu m excess. The distributions of the
spiral galaxies and the dwarfs overlap in Figure 2, but the dwarf sample extends to much redder [3.6] − [24] colors as well as redder [3.6] − [4.5] colors than the spirals. The dwarf galaxies with the redder colors tend to have lower metallicities, however, some low-metallicity galaxies have blue Spitzer colors. Thus, low metallicity appears to be a necessary but not sufficient condition for red [3.6] − [4.5] and [3.6] − [24] colors.

4. STELLAR [3.6] − [4.5] COLORS FROM POPULATION SYNTHESIS

To test whether stars alone can account for the variations in [3.6] − [4.5] colors, we used the Starburst99 stellar population synthesis code (Leitherer et al. 1999) to produce model stellar colors in these bands. We used version 5.1 of this code, which includes the Padova AGB stellar evolution models (Vázquez & Leitherer 2005). We note that this code does not model red supergiants in low-metallicity systems well (Vázquez & Leitherer 2005), which introduces some uncertainty to our results. We used a grid of models with ages that range from 1 Myr to 20 Gyr, and metallicities of 1/50, 1/5, 1/2.5, 1, and 2.5 times solar.

Dwarf galaxies have a large range of mass-normalized star formation rates; some are undergoing violent bursts of star formation, while others have low current rates (Hunter 1997). The integrated UBV colors of dwarf irregular galaxies are generally consistent with constant star formation rates (Hunter & Gallagher 1985; van Zee 2001). BCD galaxies are undergoing recent starbursts, but an older population is usually also present (Shulte-Ladbeck et al. 1998, 2001; Drozdovsky et al. 2002; Kong et al. 2003; Thuan & Izotov 2005). As limiting cases to the true star formation histories of the galaxies, we therefore ran both continuous and instantaneous burst star formation models.

We integrated the Starburst99 model spectra over the Spitzer bandpasses and calculated the [3.6] − [4.5] colors. In Figure 3, we plot model [3.6] − [4.5] colors versus age for various metallicities. In Figure 3, we only include stellar contributions to the Spitzer fluxes; no dust emission or interstellar gas emission lines are included. The models shown in Figure 3 also do not have reddening due to dust extinction included (see Section 6). Color corrections are also not included, as these are expected to be very small (see IRAC Data Manual). In the top panel, we present instantaneous burst models, while the bottom panel shows continuous star formation models.

Figure 3 shows that, according to Starburst99, there is a relatively small spread in the [3.6] − [4.5] colors of stars of different ages and metallicities, ≤ 0.2 mag. As expected, there is a trend such that younger (< 6 × 10^6 Myr) and lower metallicity systems (except > 2.5 Z☉) have redder colors than intermediate age systems (< 10^8 Myr). However, the spread in colors is quite small, and cannot account for the full range of observed colors for dwarfs. Except for very young (< 5 Myr) models with greater than solar metallicity, the model stellar colors are between −0.16 and 0.04. Of our dwarf galaxies, 70% are redder than this limit. Thus, the observed range in [3.6] − [4.5] colors of dwarfs is not due solely to variations in star colors due to age and metallicity variations.

5. BRα CONTRIBUTIONS TO THE 4.5 μm SPITZER BAND

In this section, we estimate the importance of the Brα line at 4.05 μm, which may contribute significantly to the Spitzer 4.5 μm band (e.g., Churchwell et al. 2004). For example, in the Galactic H ii region M17, Brα is estimated to contribute 20% of the total 4.5 μm broadband flux (Povich et al. 2007). At low metallicities, stars are hotter and therefore more ionizing photons are available for the same mass of stars. Thus, as metallicity decreases, for the same star formation rate the Hα and Brα fluxes are expected to increase (e.g., Charlot & Longhetti 2001; Lee et al. 2002).

To determine how much Brα can affect the [3.6] − [4.5] color, we added Brα to the Starburst99 models shown in Figure 3. We used the Hα fluxes provided by Starburst99, along with a nominal Brα/Hα ratio of 0.0273 (10,000 K, Case B; Hummer & Storey 1987). We then added this model Brα flux to the Starburst99 stellar spectrum and integrated over
the Spitzer bandpasses to get model colors. In Figure 4, we plot the \([3.6] - [4.5]\) model color including Br\(\alpha\) against age, with different metallicity models plotted with different symbols. These models do not include dust extinction or emission, or other interstellar lines besides Br\(\alpha\). A comparison of Figure 4 to Figure 3 shows that, in some very young systems, Br\(\alpha\) can contribute significantly, particularly for low-metallicity systems. For example, for ages \(\lesssim 10\) Myr and a metallicity of \(1/50\) solar, Br\(\alpha\) may redden the \([3.6] - [4.5]\) color by \(\gtrsim 1\) mag. A higher assumed temperature will decrease this reddening somewhat.

A more direct way to determine the Br\(\alpha\) contribution to the observed 4.5 \(\mu\)m flux is to either measure it directly, or to extrapolate from Br\(\gamma\) or H\(\alpha\) measurements. Only one galaxy in our sample, II Zw 40, had a total-galaxy Br\(\alpha\) flux available (Verma et al. 2003). From this measurement, we find that only \(\sim 11\%\) of the Spitzer 4.5 \(\mu\)m flux of II Zw 40 is due to Br\(\alpha\). Another galaxy in our sample has a total-galaxy published Br\(\gamma\) flux available (SBSG 0335–052; Dale et al. 2001). Using the small-aperture spectroscopic Br\(\alpha\)/Br\(\gamma\) flux ratio from Vanzi et al. (2000) and Hunt et al. (2001) to extrapolate to the total Br\(\alpha\) flux, we estimate that the Br\(\alpha\) contribution to the 4.5 \(\mu\)m Spitzer flux for this galaxy is \(\sim 31\%\). This may be an overestimate, since some of the Br\(\gamma\) flux may arise in less extincted regions (e.g., Vanzi et al. 2000).

For NGC 5253, the Br\(\alpha\) measurement of Kawara et al. (1989) in a \(10' \times 20'\) aperture gives a lower limit to the Br\(\alpha\) contribution to the Spitzer 4.5 \(\mu\)m flux of 2\%. This aperture is considerably smaller than the optical angular size for NGC 5253 of \(\sim 2' \times 5'\) given in the NASA Extragalactic Database (NED) and the observable extent of the 3.6 \(\mu\)m emission in the archival Spitzer image of \(\sim 1' \times 2'\). However, the infrared emission is strongly centrally peaked in the archival Spitzer images, with 25\% of the total 3.6 \(\mu\)m flux and 47\% of the 4.5 \(\mu\)m flux within a \(10' \times 10'\) region. Thus, the Br\(\alpha\) contribution to the 4.5 \(\mu\)m flux is likely not much more than 4\%–8\% for NGC 5253.

For galaxies with published total-galaxy H\(\alpha\) measurements, we estimate the Br\(\alpha\) contribution indirectly from these fluxes, correcting for internal extinction using the published H\(\alpha\)/H\(\beta\) ratio. From the extinction-corrected H\(\alpha\) flux, we calculated the Br\(\alpha\) flux, and determined the fraction of the observed 4.5 \(\mu\)m broadband flux due to Br\(\alpha\). This calculation shows that, if the H\(\alpha\)/H\(\beta\) estimates of extinction are appropriate, for our sample galaxies the fraction of the observed Spitzer flux due to Br\(\alpha\) ranges from 0.3\% to 23\%, with most (80\%) having less than 10\% of their total 4.5 \(\mu\)m flux due to Br\(\alpha\). In some cases, H\(\alpha\)/H\(\beta\) may underestimate the extinction (see Section 6), thus these percentages are lower limits.

We then re-calculated the \([3.6] - [4.5]\) colors of the galaxies, after removing the flux due to Br\(\alpha\). In the left panel of Figure 5,
for the dwarf galaxies with published Hα fluxes, we plot the metallicity against both the observed and the Brα-removed [3.6] – [4.5] colors. For the galaxies with measured Brα or Brγ, we plot two Brα-corrected values, one calculated using the Hα (filled red squares) and one using the Brα or Brγ value (open green triangles). In Figure 5, we mark the range in [3.6] – [4.5] expected from starlight alone, −0.16 ≤ [3.6] – [4.5] ≤ 0.04 (see Figure 3). The correction for Brα shifts the galaxies to the left, to bluer [3.6] – [4.5] colors, with the shifts ranging from 0 to 0.3 mag. Note that for II Zw 40 and SBSG 0335–052, the Brα correction inferred from Hα and Hα/Hβ measurements is less than that determined from a direct Brα measurement (in the case of II Zw 40) or from Brγ (for SBSG 0335–052). This suggests that the Hα/Hβ ratio may underestimate the extinction in some cases (see Section 6).

Most of the shifts seen in Figure 5 are relatively small, ≤ 0.1 mag. However, for a few of our galaxies (for example, He 2–10), the shifts are sufficient to move the galaxies into the range expected from starlight. In these cases, Brα may be mainly responsible for the red [3.6] – [4.5] colors.

However, for some of our sample galaxies (e.g., II Zw 40, SBSG 0335–052, HS 0822+3542, NGC 4194, and SHOC 391), the Brα-corrected colors are still redder than those expected by starlight alone. For II Zw 40, this conclusion is particularly robust, because a direct Brα measurement is available (Verma et al. 2003). For SBSG 0335–052, the Brγ observations of Dale et al. (2001) also provide a reasonably strong constraint.

In the right panel of Figure 5, a similar plot is shown for the spiral sample. The open black circles are the published [3.6] – [4.5] values, while the red crosses show the values after correction for Brα, calculated using the total-galaxy Hα fluxes and the Paα/Hα ratio for the inner 50′′ (Calzetti et al. 2007). This plot shows that for normal spirals the corrections for Brα in the Spitzer 4.5 μm filter is generally very small, consistent with the fact that most of the published [3.6] – [4.5] values are in the expected range for starlight.

6. REDDENING OF STARLIGHT IN THE SPITZER BANDS DUE TO DUST EXTINCTION

Another possible source of reddening of the [3.6] – [4.5] color is dust extinction of the starlight. The model [3.6] – [4.5] colors of stars shown in Figure 3 do not include reddening due to dust extinction. In modeling the spectral energy distributions in galaxies, reddening is sometimes neglected at wavelengths > 3.6 μm (e.g., Draine et al. 2007). However, if the infrared sources are highly obscured, reddening by extinction may be important, even in the Spitzer bands.

How much reddening is present depends upon the properties of the dust grains, and therefore the extinction law, as well as the geometry of the system. The ratio of visual extinction to B − V reddening $A_V/E(B−V) = R_V$ has been found to vary from ~3.1 in diffuse gas to ~5.5 in dense clouds (e.g., Cardelli et al. 1989). The extinction law in the Spitzer bands also varies with optical depth (Chapman et al. 2008). Combining the extinction laws from these papers gives a range for $A_V/E(3.6−4.5)$ between ~41 for diffuse gas to ~68 for more extincted regions.

The published Hα/Hβ ratios for our sample dwarfs imply $A_V$ between 0 and 2.5, or reddening in [3.6] – [4.5] of less than 0.06 mag, not sufficient to account for the 4.5 μm excess in our reddest systems. However, there is evidence that the Hα/Hβ ratio strongly underestimates the extinction in at least some of our systems.

The Hα/Hβ ratio of SBSG 0335–052, the galaxy in our sample with the reddest [3.6] – [4.5] color, implies only $A_V ∼ 0.3–0.5$ (Izotov et al. 1997, 2007). However, mid-infrared spectroscopy of SBSG 0335–052 shows a deep 9.7 μm silicate absorption feature (Thuan et al. 1999; Houck et al. 2004), suggesting a much higher optical depth of $A_V ∼ 15–20$. The Brγ/Brα ratio also suggests a much larger extinction than that...
implied by the Hα/Hβ ratio, $A_V \sim 12$ (Hunt et al. 2001). Dust modeling of the 6–100 μm spectral energy distribution also suggests that most of the mid-infrared emission originates from a highly obscured ($A_V \sim 12–30$) luminous star cluster (Hunt et al. 2001, 2005; Plante & Sauvage 2002; Takeuchi et al. 2003). The increase in derived extinction with wavelength suggests that most of the mid-infrared emission originates from a highly obscured ($A_V \sim 12–30$) luminous star cluster (Hunt et al. 2001, 2005; Plante & Sauvage 2002; Takeuchi et al. 2003). The increase in derived extinction with wavelength implies a more complex geometry than a simple uniform foreground screen of dust, and suggests that the light seen in the optical is less obscured than the bulk of the starburst (e.g., Hunt et al. 2001; Reines et al. 2008). The 3–4 μm source in SBSG 0335–052 is very compact, $<1^\prime\prime$ (Hunt et al. 2001), consistent with this picture. If the extinction obtained from the silicate absorption, $A_V \sim 15–20$, applies to the majority of the stars contributing to the 3.6 and 4.5 μm emission, then $E(3.6 – 4.5) \sim 0.22–0.48$. Combined with Brα, this can account for some, but not all, of the observed reddening in [3.6] – [4.5].

In the left panel of Figure 6, we plot the oxygen abundance of the sample dwarf galaxies against the [3.6] – [4.5] color, after this color has been corrected for both Brα and reddening of the starlight due to extinction. For these galaxies, we plot extinction corrections made using the 9.7 μm silicate optical depth and the Brα/Brγ ratio (magenta asterisks), and/or the Hα/Hβ ratio (black filled diamonds), depending upon the available data. As in Figure 5, we have marked the expected colors due to starlight alone. Note that the [3.6] – [4.5] color of SBSG 0335–052 is too red to be accounted for by stars, even after correcting for both Brα and extinction. Thus, there must be another contributor to the 4.5 μm excess for this galaxy.

A similar situation may exist for II Zw 40. The Hα/Hβ ratio implies $A_V \sim 1.1$ (French 1980; Kinman & Davidson 1981), or $E(3.6 – 4.5) \sim 0.03$. However, longer wavelength data give higher extinctions. The Brα/Brγ ratio gives $A_V \sim 10$ (Verma et al. 2003), while comparison of Brγ to radio continuum implies $A_V \sim 8–10$ and modeling of the infrared spectral energy distribution gives $A_V \sim 20–30$ (Hunt et al. 2005). As with SBSG 0335–052, the mid-infrared source in II Zw 40 is very compact, with most emission confined to $0.5\prime\prime$ (Beck et al. 2002). In contrast to SBSG 0335–052, however, no silicate absorption feature is seen in mid-infrared spectra of II Zw 40 (Martín-Hernández et al. 2006; Wu et al. 2006), thus the extinction is uncertain. If $A_V \sim 10$ holds for the bulk of the population contributing to the Spitzer broadband flux, then $E(3.6 – 4.5) \sim 0.15–0.24$. As shown in Figure 6, this could account for some, but not all, of the observed reddening.

NGC 5253 is another example of a galaxy with a larger implied optical depth from the Brα/Brγ ratio ($A_V \sim 11$ in a $10\prime\times 20\prime\prime$ beam; Kawara et al. 1989) and the silicate absorption ($A_V \sim 8–25$ in a $5\prime.4$ aperture; Aitken et al. 1982) than from the Hα/Hβ ratio ($A_V \sim 0.3$ for the whole galaxy; Moustakas & Kennicutt 2006). As with II Zw 40 and SBSG 0335–052, extinction and Brα together cannot account for all of the reddening in [3.6] – [4.5] (see Figure 6). As noted in Section 5, however, our correction for Brα may be slightly too small.

For He 2–10 (ESO 495-21), if the silicate absorption ($A_V \sim 15$ in a $5\prime.9$ aperture; Phillips et al. 1984) or the Brα/Brγ–implied extinction ($A_V \sim 17$ in $7\prime.1 \times 3\prime.5$ aperture; Kawara et al. 1989) are used to correct the Spitzer colors, instead of the extinction implied by the Hα/Hβ ratio ($A_V \sim 1.7$; Vacca & Conti 1992), the corrected [3.6] – [4.5] color becomes too blue (see Figure 6). In this galaxy, the lower extinction estimate may be more appropriate.

Two of our other dwarfs with red [3.6] – [4.5] colors, NGC 4194 and Haro 11 (ESO 350-38), also show apparent silicate absorption in their mid-infrared spectra (Brandl et al. 2006; Wu et al. 2006). For Haro 11, no silicate optical depth analysis has been done yet. For NGC 4194, the silicate optical depth is estimated to be $\tau_{9.7} = 0.37$ (Brandl et al. 2006). Assuming $A_V/A_{9.7} \sim 18.5$ (Roche & Aitken 1984) gives $E(3.6 – 4.5)$ between 0.10 and 0.17. Combined with the correction for Brα, this can account for most, but not all, of the excess 4.5 μm emission (see Figure 6).
In contrast to these galaxies, I Zw 18 shows no silicate absorption (Wu et al. 2007) and the extinction implied by the \( \text{H} \alpha / \text{H} \beta \) ratio is very small (Cannon et al. 2002). In this case, the correction for extinction is small compared to that for \( \text{Br} \alpha \) (see Figures 5 and 6).

One caveat in this analysis is that the reddening of the stars in a galaxy may differ significantly from that of the ionized gas, depending upon the geometry of the system. Thus, caution should be taken in applying extinction corrections obtained from emission line ratios or silicate absorption features to stellar colors. Furthermore, for different galaxies different data sets are available.

In the right panel of Figure 6, the blue open diamonds show the \([3.6] - [4.5]\) colors of the normal spirals after correction for both \( \text{Br} \alpha \) and for starlight reddening. The latter term was calculated using the \( \text{Pa} \alpha / \text{H} \alpha \) ratios of Calzetti et al. (2007). Note that these corrections are small for the spirals, with \( A_V \) ranging from 0.2 to 2.5. Thus, the correction for starlight reddening, like that for \( \text{Br} \alpha \), does not shift the spirals much on this plot. We note that other techniques for obtaining extinctions such as background counts of galaxies through galaxian disks also give relatively small average obscurations for nearby spirals (White et al. 2000), consistent with the above range in \( A_V \) for spirals (see also Calzetti 2001).

7. CONTRIBUTIONS FROM THE NEBULAR CONTINUUM

Another source of near-to-mid-infrared light in galaxies is nebular continuum emission, which we have neglected so far in our analysis. In the case of low-metallicity starburst systems, this component can be important (Joy & Lester 1988; Krüger et al. 1995; Vanzi et al. 2000; Hunt et al. 2001). To determine the contribution from the gaseous continuum to the \textit{Spitzer} bands, we ran another set of Starburst99 models, including just starlight and the gaseous nebular continuum, excluding \( \text{Br} \alpha \) and dust reddening. To calculate the gaseous continuum, Starburst99 uses parameters from Ferland (1980). The longest wavelengths used in these tables is 4.5 \( \mu \text{m} \), therefore the predicted values of the nebular continuum are unreliable at longer wavelengths (Leitherer et al. 1999).

In Figure 7, we plot the model \([3.6] - [4.5]\) colors as a function of age for various metallicities. Comparison with Figure 3 shows that the addition of nebular continuum emission significantly reddens the \([3.6] - [4.5]\) colors of young systems, particularly for low metallicities. For example, < 10 Myr 0.02 \( Z_\odot \), instantaneous burst models with the nebular continuum included have \([3.6] - [4.5]\) colors about 0.5 mag redder than models without this component. For solar metallicities, ages \( \leq 4 \) Myr produce such red colors. Thus, the nebular continuum may be a very important component in very young and/or low-metallicity systems.

In extreme cases, the nebular continuum may dominate not only the 4.5 \( \mu \text{m} \) band, but also the 3.6 \( \mu \text{m} \) band. This is illustrated in Figures 8 and 9, where we plot the ratio of the nebular continuum flux in the 3.6 \( \mu \text{m} \) and 4.5 \( \mu \text{m} \) bands to the flux from starlight plus the nebular continuum, for the models shown in Figure 7. Figures 8 and 9 show that, for solar metallicity and ages \( \leq 3 \) Myr, and for 0.02 \( Z_\odot \) and \( \leq 10 \) Myr, contributions to both bands from the nebular continuum are larger than from starlight. Krüger et al. (1995) found that, for a 5 Myr 0.02 \( Z_\odot \) burst, \( \sim 70\% \) of the flux in the \( L \) band is due to the nebular continuum, consistent with these plots. Since the nebular contributions are typically larger at 4.5 \( \mu \text{m} \) than 3.6 \( \mu \text{m} \), the net effect is a reddening of the observed colors of galaxies. The issue of non-stellar emissions at 3.6 \( \mu \text{m} \) is discussed further in Section 8.

To determine the contribution from the nebular continuum for individual galaxies in our sample, we require an estimate of the average age of the stellar population. We do this two ways. First, we use Starburst99 models and published \( \text{H} \beta \) equivalent widths to estimate the age. For each galaxy, we...
use models with a metallicity closest to that of the published metallicity, and we fit both instantaneous and continuous star formation models. Second, when sufficient broadband optical data is available ($\geq$3 filters), we fit the optical spectral energy distribution to Starburst99 models to get the age and extinction data is available (metallicity, and we fit both instantaneous and continuous star formation models with a metallicity closest to that of the published model.

The results of Starburst99 models showing the ratio of the flux in the 4.5 $\mu$m band from the nebular continuum to that from starlight plus nebular continuum. The symbols are as in Figures 3, 4, 7, and 8. No Br$\alpha$ is included.

![Figure 9](image.png)

Figure 9. The results of Starburst99 models showing the ratio of the flux in the 4.5 $\mu$m band from the nebular continuum to that from starlight plus nebular continuum. The symbols are as in Figures 3, 4, 7, and 8. No Br$\alpha$ is included.

In Figure 10, the nebular-corrected $[3.6] - [4.5]$ colors are plotted against oxygen abundance, with the dwarfs in the left panel and the spirals in the right. In these plots, the filled upside-down magenta triangles are the nebular continuum-corrected colors calculated using the best-fit ages from the H$\beta$ equivalent widths, while the cyan open diamonds are the nebular-corrected values using the best-fit ages from the broadband optical fitting. To illustrate the uncertainties in this correction, the open red circle shows the color after correction for nebular emission using the best-fit age from the broadband fitting minus the 1$\sigma$ uncertainty in the age. In some cases, the corrections to the Spitzer $[3.6] - [4.5]$ color due to the nebular continuum is quite large, for example, it is $\sim$0.4 mag for SBSG 0335–052.

In most cases, within the uncertainties the combined contributions of Br$\alpha$, reddening due to dust extinction, and the nebular continuum can account for all of the observed reddening above starlight. In Figure 10, for all of the galaxies except two, the two estimates of the corrected color (the magenta upside-down filled triangle and the cyan open diamond) are within the green hatched region, or span this region. For the two exceptions, the data sets are incomplete, thus we cannot make firm conclusions. For Haro 11, as noted in Section 6, silicate absorption may be present in the Spitzer spectrum (Wu et al. 2006), however, no optical depth has been published, and no published Br$\alpha$ or Br$\gamma$ values are available. For SHOC 391, no Br$\alpha$, Br$\gamma$, or silicate absorption measurements are available. Thus, the extinction of the starlight and/or the correction for Br$\alpha$ in the Spitzer 4.5 $\mu$m band may be underestimated for these galaxies.

8. NON-STELLAR CONTRIBUTIONS TO THE 3.6 $\mu$m BAND

It is often assumed that the 3.6 $\mu$m band is dominated by starlight, and a standard $[3.6] - [4.5]$ spectrum is assumed for the stellar component, which is then subtracted from the observed 4.5 $\mu$m flux to get the residual 4.5 $\mu$m emission (e.g., Helou et al. 2004; Engelbracht et al. 2005; Dale et al. 2005). However, as noted above, nebular continuum emission may be important at both 3.6 $\mu$m and 4.5 $\mu$m (see Section 7). Also, if hot dust is significant at 4.5 $\mu$m, it may also be present at 3.6 $\mu$m, and even at 2 $\mu$m (e.g., Lu et al. 2003).

To test whether significant non-stellar emission is present at 3.6 $\mu$m in individual galaxies in our sample, we used our Starburst99 fits to the broadband optical data. For all but one of the galaxies with available optical data, we cannot rule out that all of the 3.6 $\mu$m emission is due to starlight, since our best-fit stellar spectra are consistent with the observed Spitzer 3.6 $\mu$m flux within the uncertainties. The only galaxy in our sample that shows a clear 3.6 $\mu$m excess above the inferred stellar continuum is the reddest galaxy in $[3.6] - [4.5]$, SBSG 0335–052 (see Figure 11; also see Galliano et al. 2008). For SBSG 0335–052, although the inferred stellar continuum is consistent with the near-infrared photometry for both the instantaneous and continuous bursts, it is about a factor of 5 below the Spitzer 3.6 $\mu$m measurement. However, when the nebular continuum is included in the Spitzer bands, most of the 3.6 $\mu$m flux can be accounted for (see Figure 11). This shows that the 3.6 $\mu$m excess may be mainly due to the gaseous continuum.

We note that the best-fit extinction for the Starburst99 model of SBSG 0335–052, $A_V = 1.0 \pm 0.5$, is significantly less than that inferred by the 9.7 $\mu$m silicate absorption feature ($A_V \sim 15–20$; Thuan et al. 1999; Houck et al. 2004). As mentioned in...
Section 6, for this galaxy, the stars that dominate the observed light in the optical may be much less obscured than the stars that dominate in the infrared. Thus, our Starburst99-derived extinction based on the optical data may not be an appropriate value to use in the infrared. A second more highly obscured stellar population, unseen in the optical, may also contribute to the observed Spitzer 3.6 μm flux of this system. However, this second population is not evident in the near-infrared data.

Unfortunately, for some galaxies in our sample, no suitable broadband optical data were available for fitting, or we were not able to get good fits to the available data with our Starburst99 models. Thus, we were not able to use this method to test for 3.6 μm excesses above the stellar continuum in these galaxies. These galaxies include some of the reddest galaxies in our sample in [3.6] − [4.5]: SHOC 391, Haro 11, Pox 4, and HS 0822+3542. Further observations and more detailed modeling of these systems are needed to search for 3.6 μm excesses above the stellar continuum.

None of the spirals in our sample for which a good fit to the optical data was found showed a 3.6 μm excess above the inferred stellar continuum. As they also have [3.6] − [4.5] colors consistent with starlight (Figure 1), this also implies little 4.5 μm non-stellar excess in the spirals. As noted earlier, the 3.3 μm PAH feature lies within the 3.6 μm Spitzer band, however, the spirals in our sample do not show unusually blue [3.6] − [4.5] colors. Thus, there is no strong evidence for a strong PAH contribution to the 3.6 μm flux of the spirals in our sample. As noted earlier, dwarf galaxies tend to have weaker PAH features than spirals, thus this conclusion also may hold for the dwarf galaxies.

An alternative way to search for 3.6 μm excesses is to compare the [3.6] − [4.5] colors with other near-to-mid-infrared colors (Figure 12). The spirals (right panel) show less scatter in these colors than the dwarfs (left panel), and the higher metallicity dwarfs (blue open squares) show less scatter than the lower metallicity dwarfs. For the dwarfs, weak correlations are seen between [3.6] − [4.5] and K − [3.6], and between [3.6] − [4.5] and H − [3.6], in that the extremely red galaxies in [3.6] − [4.5] also tend to be red in these other colors. This...
VSG excitation is enhanced.

that PAHs are destroyed in hard UV fields, while mid-infrared
not expected to vary much within a dwarf galaxy, this indicates
[Ne\text{\textsc{ii}}]

suggests that non-stellar contributions at 3.6 $\mu$m may be present
in these systems. The correlation seen between [3.6] – [4.5]
and $K$ – [4.5] is not unexpected, if $K$ roughly traces the older
stellar population. No correlation is seen between [3.6] – [4.5]
and $H$ – $K$.

9. CONTRIBUTIONS AT 4.5 $\mu$m FROM HOT INTERSTELLAR DUST

It is often assumed that excess emission at 4.5 $\mu$m is due
to hot dust (e.g., Engelbracht et al. 2005; Hunter et al. 2006).
However, Figure 10 shows that, for all the galaxies in our sample
with sufficient data available, a combination of Br$\alpha$, the nebular
continuum, and dust reddening may be able to account for most
of the 4.5 $\mu$m excess. Thus, a major contribution from dust
emission is not required. However, with the available data, given
the uncertainties we are not able to completely rule out hot dust
emission in the 4.5 $\mu$m band.

One way to distinguish between these different processes
is with spectroscopy. However, at the present time, few high
signal-to-noise ratio (S/N) spectra of galaxies in the 3–5 $\mu$m
range are available, since the Spitzer spectrometers do not reach
wavelengths $\lesssim$4.9 $\mu$m. Co-added Infrared Space Observatory
(ISO) 2.5–4.9 $\mu$m spectra of disk galaxies show a continuum
excess with a color temperature of $\sim$1000 K (Lu et al. 2003).
At longer wavelengths, in the $\sim$24 $\mu$m range, the continuum
emission from star-forming galaxies is attributed to “very small
grains” (VSGs; Désert et al. 1990). In Galactic H\text{\textsc{ii}} regions,
the 6–16 $\mu$m VSG continuum is strong, in contrast to the PAH
features which weaken in H\text{\textsc{ii}} regions (Cesarsky et al. 1996;
Peeters et al. 2004). Within dwarf galaxies, the ratio of the PAH
feature strength to the VSG continuum varies spatially, being
anticorrelated with the [Ne\text{\textsc{iii}}] 15.8 $\mu$m/[Ne\text{\textsc{ii}}] 12.8 $\mu$m
line ratio (Madden et al. 2006; Beirao et al. 2006). Since [Ne\text{\textsc{iii}}]/
[Ne\text{\textsc{ii}}] is a measure of radiation field hardness, and metallicity is
not expected to vary much within a dwarf galaxy, this indicates
that PAHs are destroyed in hard UV fields, while mid-infrared
VSG excitation is enhanced.

In a few low-metallicity galaxies with spatially resolved
ISO spectra, the short-wavelength end (4.9–5.6 $\mu$m) shows
strong continuum emission in regions with strong H$\alpha$
emission (Madden et al. 2006). This supports the idea that the VSG
continuum may extend well into the 3–5 $\mu$m range. For SBSG
0335–052, a Spitzer spectrum shows a 5 $\mu$m continuum $\sim$2 mJy
(Houck et al. 2004). Extrapolation of this to shorter wavelengths
could possibly account for much of the observed 4.5 $\mu$m
broadband emission. Three of our galaxies with very red [3.6]
– [4.5] colors, SBSG 0335–052, Haro 11, and SHOC 391, have
been classified as “mid-infrared peakers” by Engelbracht et al.
(2008), having infrared spectral energy distributions that peak
near 24 $\mu$m rather than in the far-infrared. This is consistent
with these galaxies having very hot dust grains on average, and
the dust continuum extending down to $\lesssim$4.5 $\mu$m.

Thus, with the available data we cannot rule out hot dust
as a contributing factor. However, the above discussion shows
that the nebular continuum can also be quite strong at these
wavelengths, thus it is hard to separate these two components
in the 3–5 $\mu$m wavelength range.

10. MORPHOLOGY

Of the 71 galaxies in our dwarf sample, 18 are classified
in the NED\textsuperscript{2} as BCDs or “compact.” 19 as irregular
(Im/I0/Irr/Ib/n/IBm/IB/In), three as Sm, and three as Sd, with
the rest listed as other types, such as H\text{\textsc{ii}} galaxies or starbursts.
In some cases, the classifications in NED differ from those in
the SIMBAD database,\textsuperscript{3} as dwarf classifications are often
subjective, and these catalogs are heterogeneous.

In the left panel of Figure 13, we plot the observed [3.6] – [4.5]
colors of the dwarfs versus log(O/H) + 12 as in Figure 1,
however, in Figure 13 the points are color coded according to the
morphological type in NED. The blue filled circles are classified

\textsuperscript{2} The NASA/IPAC Extragalactic Database (NED) is operated by the Jet
Propulsion Laboratory, California Institute of Technology, under contract with the
National Aeronautics and Space Administration.

\textsuperscript{3} http://simbad.u-strasbg.fr/simbad, operated at CDS, Strasbourg, France.
as blue compact galaxies or as compact, while the magenta open diamonds are classified as BCD galaxies or as compact, while the magenta open diamonds are listed as Irr, Im, I0, IB, or IAB. The green crosses are galaxies classified as other types such as H[3.6] with other classifications. In the right panel of Figure 13, we plot diamonds are listed as irregular. The green crosses are galaxies as blue compact galaxies or as compact, while the magenta open colors. The observation that the reddest galaxies tend to be Spitzer colors. The points in Figure 14(a) are color coded according to their morphological type in NED, as in Figure 13.

The reddest systems also show evidence for interactions or mergers: I Zw 18 (van Zee et al. 1998), SBSG 0335–052 (Pustilnik et al. 2001), Haro 11 (Östlin et al. 2001), HS 0822+3542 (Pustilnik et al. 2003; Corbin et al. 2006), NGC 4194 (Armus et al. 1990), and II Zw 40 (Baldwin et al. 1982). This is consistent with the idea that an interaction or merger has driven gas into the center of the system, causing very centrally concentrated star formation. This may lead to very intense UV fields and/or high optical depths, causing hotter dust grains, more 24 μm emission, more reddening due to extinction, more gaseous continuum emission, and/or more Brγ.

In our earlier Spitzer study of more massive interacting galaxies (Smith et al. 2007), we did not find a statistically significant difference between their [3.6] − [4.5] colors and the colors of normal spirals. However, that sample was selected to be early-stage encounters, with the disks widely separated, while some of the dwarfs in the current sample may be more advanced interactions.

11. SPITZER LUMINOSITIES AND STELLAR MASSES

For irregular and dwarf elliptical galaxies, a correlation between blue luminosity and oxygen abundance has been observed (e.g., Skillman et al. 1989), and interpreted as a mass–abundance relation. For irregulars, this relation has been extended to the 4.5 μm luminosity by Lee et al. (2006), who found less scatter at 4.5 μm than at B, and concluded that the 4.5 μm band is a better tracer of stellar mass than the B band.

In the left and right panels of Figure 14, we compare the 4.5 μm luminosity with log(O/H) + 12 for our sample dwarfs and normal spirals, respectively. For consistency with previous work, we use the “monochromatic” luminosity νLν, with frequency 6.67 × 1015 Hz. The luminosities were calculated using distances from NED calculated with H₀ = 73 km s⁻¹ Mpc⁻¹, and Virgo/Great Attractor/Shapley cluster infall, except in the case of NGC 6822, where this method fails. For NGC 6822, we use the Cepheid distance from Paturel et al. (2002). As expected, the 4.5 μm luminosities of the dwarf sample are typically much lower in than for the spirals, but there is some overlap in range. The points in Figure 14(a) are color coded according to their morphological type in NED, as in Figure 13.

In Figure 14, we include the best-fit line from Lee et al. (2006) for their irregular galaxies. Figure 14 shows that most of our sample galaxies, and all of our irregulars, lie near the Lee et al. (2006) line. However, a handful of galaxies show large excesses in 4.5 μm luminosity for their metallicities. These include some of the systems noted earlier for having very red [3.6] − [4.5] colors: SBSG 0335–052, SHOC 391, Haro 11, and I Zw 18. In contrast, some of the galaxies with red [3.6] − [4.5] colors, such as II Zw 40, lie close to the Lee et al. (2006) line. In addition, a few other galaxies that are less extreme in [3.6] − [4.5] also show up as discrepant in Figure 14: SHOC 567, Tol 2138-405, and UM 420. Tol 2138-405 and SHOC 567, like the redder galaxies, have peculiar morphologies indicative of interactions (Telles et al. 1997; Kniazev et al. 2004). UM 420 lies behind a foreground elliptical galaxy (Salzer et al. 1989), thus the published Spitzer flux may be confused.

Figure 14 shows that for extreme starbursts, compact systems, and/or interacting systems, the 4.5 μm luminosity may not be a
good tracer of stellar mass. This may be in part due to non-stellar contributions in the 4.5 $\mu$m band. Alternatively, an interaction or merger may have driven unprocessed gas into the central region of these galaxies, lowering their metallicity relative to their stellar mass (e.g., Rupke et al. 2008).

In Figure 15, we plotted the 3.6 $\mu$m luminosity versus oxygen abundance for both the dwarfs and the spirals. Again, a correlation is seen, in that higher luminosity systems tend to have higher metallicities. However, as in Figure 14, there are some galaxies with too high luminosities for their metallicities. These are the same galaxies that are discrepant in Figure 14, thus these galaxies may also have large non-stellar excesses at 3.6 $\mu$m, or may have lowered metallicities due to interactions or mergers.

12. DISCUSSION

For the dwarf galaxies in our sample, we find that lower metallicity systems tend to have redder [3.6] − [4.5] colors than higher metallicity systems, in that systems with log(O/H) + 12 < 8.2 tend to be redder on average. Comparison to stellar population synthesis models shows that the observed colors of many dwarfs are too red to be accounted for solely by unobscured starlight.

For all of the galaxies in our sample with sufficient data available, a combination of Brγ emission, reddening by dust, and nebular emission can account for the observed 4.5 $\mu$m excess. Nebular continuum emission, which is often neglected in discussions of the Spitzer colors of galaxies, may contribute to both the 3.6 $\mu$m and 4.5 $\mu$m bands, and in extreme cases can dominate the observed fluxes in these bands. As seen in Figure 2, 4.5 $\mu$m excess is correlated with the mass-normalized 24 $\mu$m luminosity and therefore with more intense UV fields.

Another factor that is sometimes ignored is reddening by dust extinction in the Spitzer bands, which can be quite large in some situations. Some of our sample galaxies show deep silicate absorption features and/or large Brα/Brγ ratios, in spite of the small extinctions implied by Hα/Hβ or optical colors. In these cases, reddening of the starlight due to dust extinction may be quite important. The situation in these very obscured dwarfs may resemble that in the starburst elliptical galaxy NGC 1377, which has a deep silicate absorption feature and a high implied optical depth (Roussel et al. 2006). NGC 1377 may contain a very young highly obscured compact starburst (Roussel et al. 2006). Like our extreme dwarfs, NGC 1377 has a very red [3.6] − [4.5] color (see Figure 16 in Smith et al. 2007).

Given the uncertainties in the data and models, we cannot rule out an additional contribution to the 4.5 $\mu$m flux from dust heated to high temperatures by very intense UV fields. This dust continuum may be the short-wavelength extension of the VSG continuum seen at longer wavelengths in ISO and Spitzer spectra of Galactic H II regions and star-forming regions in dwarf galaxies. At the present time, the nature of the grains responsible for this 4.5 $\mu$m dust emission is unclear. According to the dust models of Draine & Li (2007), the grains responsible for the continuum at 6–30 $\mu$m have sizes ∼15–40 Å, and may be large PAHs ($N_C ∼ 2000–3 \times 10^4$). Draine & Li (2007) concluded that in most cases this continuum emission is due to single-photon heating, however, in the case of very intense UV radiation fields, a particle may not cool completely before absorbing another photon. In this case, higher temperatures are reached, and the peak of the VSG spectrum moves to shorter wavelengths. In sources with strong 4.5 $\mu$m continuum, the particles may be larger and/or hotter, and possibly may be in thermal equilibrium with a hard intense UV field.

It is unclear how the grains that produce the strong 6–30 $\mu$m continuum in H II regions are related to the carriers of the ∼2–3.7 $\mu$m continuum found by Sellgren et al. (1983) in reflection nebulae, which was attributed to small grains (∼10 Å) stochastically heated to ∼1000 K by UV or optical photons (Sellgren 1984). The ambient UV fields in these two environments are quite different. An & Sellgren (2003) suggest that the near-
infrared continuum-producing particles in reflection nebulae may be PAHs that are larger, more ionized, and/or more dehydrogenated than those that produce the 3.3 μm PAH feature, or may require higher energies for excitation.

Interestingly, a 4.5 μm excess has also been found for the diffuse Galactic interstellar medium. Draine & Li (2007) found that the Flagey et al. (2006) Spitzer broadband measurements of diffuse Milky Way dust are consistent with standard dust models, except for the 4.5 μm flux, which is too high by a factor of ~1.6. Flagey et al. (2006) and Draine & Li (2007) conclude that there is a “near-infrared continuum” which contributes at 4.5 μm and 3.6 μm. Furthermore, Li & Draine (2001) compared their dust models to high Galactic latitude emission as seen by DIRBE, and found a 4.9 μm excess (~2.5×). They suggested an additional form of opacity at these wavelengths, for example, carbon chains (e.g., Allamandola et al. 1999). It is unclear whether the particles that produce this 4–5 μm excess in the diffuse interstellar medium (ISM) are the same as those that are responsible for the excess in dwarf galaxies.

As noted by Engelbracht et al. (2005) and Draine et al. (2007), there appears to be a sharp change in the 8/24 μm flux ratio of galaxies at log(O/H) + 12 = 8.2 (~1/3 solar), in that this ratio abruptly decreases at this metallicity, perhaps because of weakening of the 7.7 μm PAH feature at low metallicities. We see an abrupt change in the [3.6] − [4.5] color near this same metallicity, suggesting that the 4.5 μm excess and the PAH deficiency are related. One possibility is that at this metallicity threshold the UV field hardens sufficiently to more efficiently destroy PAHs, and at the same time produces more Brα, more infrared nebular continuum, and/or more effectively excite the carriers of 4.5 μm dust emission. A second possibility is that the destruction of the carriers of the PAH emission features produces the particles that are responsible for a 4.5 μm dust continuum.

A third possibility is that there is an abrupt change in the chemistry of the interstellar matter at this metallicity, leading to both a deficiency in PAHs and to a larger percentage of grains that are more effective at radiating in the 4.5 μm regime. For example, the galaxian chemical evolution model of Galliano et al. (2008) shows a time delay between the production of silicate dust grains in supernovae and the formation of carbon-rich material in AGB stars, which can account for the relative deficiency of PAHs at low metallicities. As noted earlier, the galaxies in our sample with extremely red [3.6] − [4.5] colors have infrared spectral energy distributions that peak near 24 μm, while other low-metallicity systems do not. Engelbracht et al. (2008) suggest that the particles responsible for far-infrared/submillimeter emission are deficient in these galaxies, or are inefficiently heated. Thus, the composition of the interstellar dust in these galaxies may be different from other low-metallicity systems.

For all of our galaxies with sufficient optical data except one, population synthesis modeling cannot rule out that most of the 3.6 μm Spitzer flux is due to the stars seen at optical wavelengths. The exception, SBSG 0335–052, either has a highly obscured stellar population unseen at optical and near-infrared wavelengths, or a strong nebular or hot dust continuum that contributes significantly at 3.6 μm as well as at 4.5 μm. A similar situation applies for a star-forming clump in the tidal tail of the interacting galaxy pair Arp 285. For this clump, population synthesis based on optical broadband data indicates an excess at both 3.6 μm and 4.5 μm fluxes above the inferred stellar continuum (Smith et al. 2008). As with SBSG 0335–052, this may be due to either a strong nebular continuum, hot dust being present at 3.6 μm, or high obscuration in the optical.

13. CONCLUSIONS

For a large sample of dwarf galaxies, we show that the Spitzer broadband [3.6] − [4.5] colors depend upon metallicity, in that lower metallicity systems (log(O/H) − 12 < 8.2) show redder colors on average than higher metallicity systems, but with much scatter. Comparison with stellar population synthesis...
models shows that starlight alone cannot account for the range of observed colors, even when accounting for variations in age and metallicity. Many galaxies have an excess at 4.5 μm compared to that expected from stars. In some galaxies, Brα contributes significantly to the observed 4.5 μm flux. In other systems, the nebular continuum plays an important role in reddening the [3.6] − [4.5] color, and in extreme cases may dominate the observed flux at both 3.6 μm and 4.5 μm. The lower metallicities in dwarfs hardens the UV field, increasing the Brα luminosity and the gaseous continuum in the infrared. In addition, high obscuration can also redden the [3.6] − [4.5] color in some cases. The combined effects of these three factors can account for the observed [3.6] − [4.5] colors of all the galaxies in our sample that have sufficient data available. Given the uncertainties, we cannot rule out an additional component from hot dust at 4.5 μm. Harder UV fields may increase the average dust temperature, increasing dust contributions at 4.5 μm. However, for our sample galaxies it does not appear to be the dominant factor.

The galaxies with the largest 4.5 μm excess are classified as BCDs, and show evidence of recent interactions and mergers with other galaxies. Such encounters may produce very concentrated star formation, causing very intense UV fields and/or high extinctions. For these galaxies, the 4.5 μm luminosity may not be a good tracer of stellar mass.

A similar analysis was done for a sample of nearby normal spirals. This showed that contributions from Brα and the nebular continuum to the 4.5 μm fluxes of normal spirals are generally small, as is reddening of the [3.6] − [4.5] starlight by dust. This is consistent with their observed [3.6] − [4.5] colors of ~0.0. For normal spirals, these bands appear to be dominated by starlight.

We thank the Spitzer team for making this research possible. This research was supported by NASA LTSA grant NAG5-13079. We thank Mark Giroux and Curt Struck for helpful communications. We also thank the anonymous referee for many helpful suggestions that greatly improved the paper. This research has made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. We acknowledge the use of the HyperLeda database at http://leda.univ-lyon1.fr.

REFERENCES

Aitken, P. K., Roche, P. F., Allen, M. C., & Phillips, M. M. 1982, MNRAS, 199, 531
Allamandola, L. J., Budgins, D. M., Bauschlicher, C. W., Jr., & Langhoff, S. R. 1999, A&A, 352, 659
An, J. H., & Sellgren, K. 2003, ApJ, 599, 312
Armus, L., Heckman, T. M., & Miley, G. K. 1990, ApJ, 364, 471
Baldwin, J. A., Spinrad, H., & Terlevich, R. 1982, MNRAS, 198, 535
Beck, S. C., Turner, J. L., Langland-Shula, L. E., Meier, D. S., Crosthwaite, L. P., & Gajjar, V. 2002, AJ, 124, 2516
Begum, A., Chengalur, J. N., Karachentsev, I. D., Kaisin, S. S., & Sharina, M. E. 2006, MNRAS, 365, 1220
Beirao, P., Brandl, B. R., Devost, D., Smith, J. D., Hao, L., & Houck, J. R. 2006, ApJ, 643, L1
Bergvall, N., & Olofsson, K. 1986, A&AS, 64, 469
Bergvall, N., & Ostlin, G. 2002, A&A, 390, 891
Bessell, M. S., Castelli, F., & Plez, B. 1998, A&A, 333, 231
Bosselli, A., et al. 1999, A&A, 335, 53
Brandl, B. R., et al. 2006, ApJ, 653, 1129
Cairós, L. M., Caon, N., Vilchez, J. M., González-Pérez, J. N., & Muñoz-Tuñón, C. 2001, ApJS, 136, 393
Calzetti, D. 2001, PASP, 113, 1449
Calzetti, D., et al. 2005, ApJ, 633, 871
