Properties of free-free, dust, and CO emissions in the starbursts of blue compact dwarf galaxies

Hiroyuki Hirashita\(^1\)⋆

\(^1\)Institute of Astronomy and Astrophysics, Academia Sinica, P.O. Box 23-141, Taipei 10617, Taiwan

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ABSTRACT

The central star-forming regions in three blue compact dwarf galaxies (He 2-10, NGC 5253, and II Zw 40) were observed in the 340 GHz (880 µm) band at ∼ 5 arcsec resolution with the Submillimetre Array (SMA). Continuum emission associated with the central star-forming complex was detected in all these galaxies. The SMA 880 µm flux is decomposed into free-free emission and dust emission by using centimetre-wavelength data in the literature. We find that free-free emission contributes half or more of the SMA 880 µm flux in the central starbursts in those three galaxies. In spite of the dominance of free-free emission at 880 µm, the radio-to-far infrared (FIR) ratios in the central star-forming regions are not significantly higher than those of the entire systems, showing the robustness of radio–FIR relation. Based on the robustness of the radio–FIR relation, we argue that the free-free fraction in the 880 µm emission is regulated by the dust temperature. We also analyze the CO (\(J = 3–2\)) emission data. We find that CO is a good tracer of the total gas mass in solar-metallicity object He 2-10. Low-metallicity objects, NGC 5253 and II Zw 40, have apparently high star formation efficiencies; however, this may be an artifact of significant dissociation of CO in the low-metallicity environments. We also point out a potential underestimate of dust mass, since the dust traced by emission is biased to the most luminous high-temperature regions, particularly when a system hosts a compact star-forming region where the dust temperature is high.

Key words: dust, extinction — galaxies: dwarf — galaxies: evolution — galaxies: individual (He 2-10, NGC 5253, II Zw 40) — H II regions — submillimetre: galaxies

1 INTRODUCTION

The early stage of galaxy evolution can be characterized by the following two properties: a poor metal abundance and a rich gas content. Although galaxies at the early evolutionary stages exist at high redshift, nearby blue compact dwarf galaxies (BCDs) are a unique category of galaxies that have those two properties in the nearby Universe (Sargent & Searle 1970; van Zee, Skillman, & Salzer 1998; Kunth &"Ostlin 2000). Some BCDs are also classified as Wolf-Rayet galaxies: the Wolf-Rayet feature indicates that the typical age of the current starburst is a few Myr (Vacca & Conti 1992; López-Sánchez & Esteban 2010).

Such intense star formation as seen in BCDs is occurring in dense and compact regions and thus can only be traced with optically thin star formation indicators, such as far-infrared (FIR) dust luminosity (e.g. Kennicutt 1998; Inoue, Hirashita, & Kamaya 2000) and radio luminosity (thermal free-free emission from H II regions plus non-thermal synchrotron emission from accelerated electrons) (Condon 1992). These two luminosities are strongly correlated in nearby star-forming galaxies (e.g. de Jong et al. 1985; Helou, Soifer, & Rowan-Robinson 1985).

In our previous paper, Hirashita (2011, hereafter H11), we observed a well studied BCD, II Zw 40, with the Submillimetre Array (SMA; Ho, Moran, & Lo 2004). In this paper, we add two BCDs, He 2-10 and NGC 5253, both of which also host high star formation activities likely to be associated with the formation of SSCs in the centre (Kobulnicky & Johnson 1999). This kind of intense star formation may also provide a relevant laboratory to understand the conditions in which high-redshift galaxies experience their first starburst episode.

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Some of the conclusions derived from II Zw 40 by H11 can be generalized by increasing the sample. H11 argues that free-free dominated submillimetre emission can be a characteristics of

\(\sum 1\) In this paper, we focus on the wavelength range (\(\lesssim 2 \, \text{cm}\)), where the radiation is optically thin for free-free absorption as far as our sample is concerned (Sections \(\sum 2\) and \(\sum 3\)).
young active star formation. H11 has clarified that, if we focus on the central star-forming region in II Zw 40, free–free emission dominates even at 880 µm. Considering that global submm luminosity is usually dominated by dust (Galliano et al. 2005), the dominance of free–free emission at 880 µm is a special characteristics, which should be examined with a larger sample.

By increasing the sample, we can also explore the metallicity dependence of various properties. The metallicity of the interstellar medium is a fundamental quantity characterizing the galaxy evolution because it reflects the enrichment in heavy elements by stellar generations. Some metallicity effects are expected in the formation of dense star-forming regions: (i) Dust-to-gas ratio in low metallicity objects is generally low (Schmidt & Bohle 1993; Eisenfeld & Ferrara 1998; Hirashita, Tajiri, & Kamaya 2002), which implies that the star-forming regions are less embedded by dust in low-metallicity objects; and (ii) in a low-metallicity (i.e. dust-poor) environment, star formation is expected to be less efficient because of less shielding of ultraviolet (UV) heating photons by dust and molecular hydrogen (Hirashita & Ferrara 2002; Yamasawa et al. 2011; Egedin & Kravtsov 2011). Thus, we will address the metallicity dependence of dust abundance and star formation efficiency by investigating gas and dust emission in BCDs.

In observing intense starburst regions associated with the formation of SSCs, a high spatial resolution is crucial to spot the young star-forming component. While high-resolution data of the central star-forming regions in BCDs are available through various radio interferometric observations with arcsecond resolutions (1 arcsec corresponds to 51 pc for He 2-10 and II Zw 40, and 18 pc for NGC 5253), information of FIR–submm dust emission on such a small scale was lacking for BCDs. We thus performed SMA observations of a few BCDs to resolve their submm emission. Shorter wavelengths such as mid-infrared can achieve almost arcsecond resolutions by single-dish telescope facilities such as the Spitzer Space Telescope Infrared Array Camera (Fazio et al. 2004) and AKARI Infrared Camera (Onaka et al. 2007), but the mid-infrared emission is dominated by stochastically heated very small grains (Draine & Anderson 1985), which are not representative of the total dust amount (although it is empirically known that the mid-infrared luminosity is well correlated with the total dust luminosity in BCDs (Wu et al. 2008; see also Takeuchi et al. 2005)).

This paper is organized as follows. We explain the observations and the data analysis in Section 2. In Section 3 we derive basic quantities related to star formation and submm emission, and discuss radio–FIR relation. We also analyze CO(3–2) emission and derive the molecular gas mass, which is used to estimate the dust-to-gas ratio and the star formation efficiency. After discussing our observational results in Section 4, we conclude in Section 5.

2 OBSERVATIONS AND DATA ANALYSIS

We selected nearby BCDs which host young compact starbursts. Searching for objects feasible for the sky coverage and sensitivity of SMA, we chose He 2-10 and NGC 5253. They have similar properties to our previous object, II Zw 40, in H11: (i) The ages of the central starbursts are young (< a few Myr) as indicated by the Wolf-Rayet feature (Vacc & Conti 1992; López-Sánchez & Esteban 2010), and the stellar spectral synthesis models (Chandar et al. 2003); and (ii) they host optically thick compact free–free emission at wavelengths > a few cm, indicating an intense starburst in a dense compact region (Turner et al. 1998; Kobulnicky & Johnson 1999; Johnson & Kobulnicky 2003). Since He 2-10 has a higher metallicity than the other two galaxies, we may be able to obtain a hint for metallicity effects (Section 2 see Table 1 for the observed metallicity values). The distances (D) and velocities (relative to the local standard of rest; V_{LSR}) adopted in this paper are listed in Table 1.

The SMA observations of He 2-10 and NGC 5253 were carried out in the 340 GHz (880 µm) band on 2012 January 11 in the subcompact configuration. Seven antennas were used with projected antenna separations between 9.5 and 45 m. The receivers have two sidebands, the lower and upper sidebands, which covered the frequency ranges from 330.8 to 334.8 GHz, and from 342.8 to 346.9 GHz, respectively. The visibility data were calibrated with the MIR package. As a flux calibrator we used Calisto (with an adopted flux of 14.5 Jy) for He 2-10, and Titan (with an adopted flux of 2.36 Jy) for NGC 5253. We used quasars J0730−116 and J1337−129 as amplitude and phase calibrators for He 2-10 and NGC 5253, respectively. We adopted quasar 3C279 as a band pass calibrator for both objects. In generating the continuum data, we excluded the chunk containing the CO(3–2) emission at rest 345.796 GHz. The calibrated visibility data were imaged and CLEANed with the MIRIAD package. The synthesized beam has a full width at half-maximum (FWHM) of 5.7 arcsec × 4.4 arcsec (290 pc × 220 pc) with a major axis position angle of 41° for He 2-10 and a FWHM of 6.7 arcsec × 4.1 arcsec (120 pc × 74 pc) with a major axis position angle of 33° for NGC 5253. The largest angular scale sampled by this observation is 19 arcsec. We also use the SMA subcompact data of II Zw 40 in H11 (see H11 for details).

Figure 1 shows the obtained continuum brightness distribution. The central active star-forming regions are detected in all the galaxies. The peak fluxes with 1 σ errors are listed in Table 1. All the sources are more extended than the beam (~ 5 arcsec), and the total fluxes are also listed in Table 1. The high brightness region (> 2σ) is concentrated, considering that the interferometry is sensitive to an extension of 19 arcsec. Hereafter, we use the term ‘central star-forming region’ to indicate the region where the SMA brightness is > 2σ. If we compare the SCUBA images of II Zw 40 and He 2-10 at 450 µm (beam size ~ 8.5 arcsec) in Galliano et al. (2005), the size of the centrally concentrated bright regions are consistent, but we miss the diffuse component (shown by the lowest contours extending ~ 1 arcmin in their figure 1). The diffuse component is also clear in their 850 µm image with a larger beam (~ 15 arcsec). We mainly analyze and discuss the SMA continuum data, although we additionally use the CO(3–2) data in Section 3.6.

In Fig. 1 the SMA 880 µm brightness distribution is overlaid with the Hubble Space Telescope (HST) Advanced Camera for Surveys (ACS) data in the optical (at F550M, F550W, and F550W bands for He 2-10, NGC 5253, and II Zw 40, respectively). The positional accuracy of our SMA image is ≤ 0.1 arcsec, while that of the HST is ~ 0.5 arcsec, limited by the positional uncertainties of the guide stars (Lasker et al. 1999). The centre of submillimetre emission coincides with that of optical for II Zw 40, while there is a significant shift in He 2-10. As shown by Kobulnicky & Johnson (1999), the 3.6 cm radio image also shows a poor correlation with the HST optical image for He 2-10. The poor positional coinci-
dence can be attributed to the extinction in the optical image. The optical image of NGC 5253 has a complicated morphology, and the peak of the SMA image does not match the brightest region in the optical. The different morphologies between optical and submm (or radio) brightnesses, especially for He 2-10 and NGC 5253, indicate that the optical light may be tracing completely different regions from those observed in submm and radio.

Submm continuum emission in galaxies is usually dominated by dust thermal radiation and contaminated by free–free emission (e.g. Galliano et al. 2005). Both these emission processes trace star-forming regions (e.g. Condor 1992). In order to separate the free–free contribution at 880 µm, we compare our submm fluxes with radio interferometric fluxes in the literature as explained in the following subsections. We neglect the non-thermal component throughout this paper since the radio spectrum at wavelengths < a few cm is consistent with free–free emission in the central star-forming regions (see each subsection below).

### 2.1 He 2-10

Kobulnicky & Johnson (1999) observed He 2-10 by the Very Large Array (VLA). Their 3.6 mm continuum image (with a beam size of 0.70 arcsec × 0.57 arcsec FWHM) fairly traces our SMA brightness, although individual knots detected in the VLA image are not resolved by our SMA observation. They also have high-resolution images at 2 and 6 cm, where the measured fluxes are 17.5 ± 0.7 mJy and 14.5 ± 0.3 mJy, respectively. The 3.6 cm flux whose (u, v) coverage is matched to these maps is 15.6 ± 0.4 mJy. These three fluxes are consistent with the flat spectrum expected for free–free emission (see also Kobulnicky & Johnson 1999). Since the spectrum at 2–6 cm is flat, a large free–free absorption at this wavelength range can be rejected. Therefore, we use the interferometric 2 cm flux (17.5 ± 0.7 mJy) to extrapolate the contribution from free–free emission at 880 µm. The flux estimated in this way may be a lower limit, since these matched data are sensitive to the compact knots and the structures surrounding them, but possibly miss the diffuse south-east extension in our SMA image (Fig. 1). This extension is just along the possible tidal tail pointed out by a CO observation in Kobulnicky et al. 1995). Thus, we also use the total VLA flux (21.1 mJy at 2 cm) as an upper limit. If we convert these fluxes to 880 µm fluxes by assuming $\nu^{-0.1}$ dependence (Osterbrock 1989), we obtain 12.8 mJy and 15.4 mJy for the lower and upper limits of the free–free contribution, respectively. These values indicate that 45–64 per cent of the SMA 880 µm flux is free–free emission.

### 2.2 NGC 5253

Meier, Turner, & Beck (2002) show that the radio continuum spectral slope of NGC 5253 is consistent with free–free emission. The slight extension to the west of the peak is common between their 3.1 mm image and our SMA 880 µm image. We adopt the total flux in the inner 20 arcsec region (54 ± 5 mJy at 3.1 mm; Meier et al. 2002), to which SMA can be sensitive. The flat spectrum at ≥ 2 cm show that free–free emission is optically thin at 3.1 mm. We estimate the 880 µm free–free flux by assuming a frequency dependence of $\nu^{-0.1}$ for the free–free spectrum. Then we obtain 48 ± 4 mJy for the contribution from free–free emission at 880 µm. Thus, 63–82 per cent of the SMA 880 µm flux is free–free emission.

### 2.3 II Zw 40

This galaxy has already been analyzed and reported in H11. The centimetre emission from the central part can be fitted by the free–free flat spectrum. Since the VLA 2 cm observation is only sensitive to the structures smaller than 4 arcsec, we also adopt the single dish flux at 2 cm (18.5 mJy; Beck et al. 2002) as an upper limit. H11 also justifies the wavelength dependence of $\nu^{-0.1}$ at ≥ 2 cm for free–free emission by spectral fitting. If we adopt 14–18.5 mJy for 2 cm flux, we obtain 10–13.5 mJy for the contribution from free–free emission at 880 µm. Thus, 64–100 per cent of the flux detected at 880 µm by SMA is free–free emission from the central star-forming region.

### 3 MODELS

In order to interpret the 880 µm emission in our sample, we need to model two major emission mechanisms (thermal free–free radiation and dust emission) from the star-forming regions. In particular, the total luminosity of dust emission (called FIR luminosity) is used to investigate the radio–FIR luminosity relation later. Physical quantities governing free–free and dust emissions are introduced. One of the basic quantities is the stellar mass ($M_*$) formed at the current episode of star formation, since the ionizing photon luminosity which determines the free–free emission and the UV luminosity which contributes to the heating of dust are proportional to $M_*$. To evaluate $M_*$, the free–free fluxes extrapolated from radio observations in Sections 2.1 and 2.3 are used (Section 3.2). The obtained $M_*$ is later used to estimate the UV luminosity in Section 3.3. In addition, we need to determine the mass and temperature of the dust to estimate the FIR luminosity, which is used to examine the radio–FIR relation. Through the modeling, we can obtain the
stellar mass formed in the current starburst episode, the dust mass (the dust optical depth), the dust temperature, all of which are basic quantities to understand the strength of starburst and the extent of dust enrichment. We use the theoretical models that we applied to II Zw 40 in our previous paper (H11). Some detailed assumptions that do not affect our results are simplified. Below we briefly summarize the models used in this paper. The same parameter values as those in H11 are adopted unless otherwise stated.

3.1 Basic setups for the star formation

In H11, we modeled the star formation rate (SFR) through the free-fall time-scale under a given gas density, while in this paper, we treat the SFR as a free parameter. This is because the SFR is more directly connected to the observed luminosity than the free-fall time and the gas density. We assume that the SFR is constant as a function of time. As shown below, since we only consider young (≲ 3 Myr) star-forming regions, the dependence of the luminosity on star formation history is weak in the sense that the total stellar luminosity is simply determined by the total stellar mass formed in the current star formation episode. We assume a Salpeter initial mass function (IMF) with a stellar mass range of 0.1–100 M⊙.

3.2 Thermal free–free emission

Free–free emission contains the information of the total stellar mass formed in the current starburst episode as modeled below. We use the free–free emission as estimated in Sections 2.1–2.3. The total stellar mass is necessary to estimate the UV luminosity based on which the FIR luminosity is modeled in Section 3.3. Thus, we first relate the free–free emission to the total stellar mass. We assume that free–free emission is optically thin since we only consider high frequencies such as ≳ 15 GHz (see Sections 2.1–2.3 for further justification).

The thermal free–free luminosity is proportional to the number of ionizing photons emitted per unit time, Nion (Condon 1992). We relate the SFR with Nion following Section 4.1 of H11 (originally, equation 1 of Hirashita & Hunt 2006). In this paper, we adopt the ionizing photon luminosity as a function of stellar mass by taking the solar metallicity case in Schaerer (2002). The dependence of Nion on the stellar metallicity is within a factor of 2 in the metallicity range concerned in this paper.

Because we mainly consider young (≲ 3 Myr) galaxies, the decline of luminosities by stellar death is small. Thus, the luminosity basically reflects the total stellar mass formed up to the current age of the system. In Fig 2 we show the evolution of the free–free luminosity (Lν) at 15 GHz normalized to the stellar mass formed (integration of the SFR over the time), which is denoted as M∗. Although we only show the results at 15 GHz, Lν at other frequencies can be estimated by assuming a frequency dependence of ∝ ν−0.1 as long as the emission is dominated by free–free and is optically thin (Sections 2.1–2.3). We assume a constant SFR, but the following results are not sensitive to the time variation of the SFR under a given M∗ as long as we consider young (≲ 3 Myr) ages. We obtain the following formula:

\[
\left( \frac{M_{\ast}}{M_{\odot}} \right) = \frac{L_{\nu}(15 \text{ GHz})}{2.45 \times 10^{13} \text{ W Hz}^{-1}},
\]

where \(L_{\nu}(15 \text{ GHz}) = 4\pi D^2 f_{\nu}(15 \text{ GHz}) [f_{\nu}(15 \text{ GHz})\text{ is the flux at }15 \text{ GHz (2 cm) adopted in Sections 2.1–2.3 and listed in Table 2.}]

This equation is not valid if there is a significant contribution from

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Figure 1. Contour: SMA 880 µm continuum brightness of (a) He 2-10, (b) NGC 5253, and (c) II Zw 40. Solid contours are 2 σ, 3 σ, ..., (1 σ = 1.15 mJy beam−1), while dotted contours are −2 and −3 σ. The beam is shown in the lower right corner. Grey scale: HST ACS optical images, at F550M, F555W, and F560W bands for He 2-10, NGC 5253, and II Zw 40, respectively.
Here we summarize the model. At submm wavelengths, the ‘large’ dust emission is distributed in a thin shell at a distance $R_{\text{dust}}$ (e.g. Galliano et al. 2005). For simplicity, we assume that the dust is concentrated within 0.2 dex if the Salpeter IMF is adopted. Following the result shown in Fig. 2 we obtain

$$L_{\text{FIR}} = 5.8 \times 10^7 \left( \frac{M_*}{M_\odot} \right) L_\odot,$$

where $M_*$ is already given by the observed radio flux through equation (1). We assume that the OB stars are located at the centre, so that we can estimate the total FIR luminosity, $L_{\text{FIR}}$, by

$$L_{\text{FIR}} = \left( 1 - e^{-\tau_{\text{dust}}} \right) L_{\text{OB}},$$

where $\tau_{\text{dust}}$ is given by equation (2). The dust temperature, $T_{\text{dust}}$, is related to the dust mass, $M_{\text{dust}}$, as

$$L_{\text{FIR}} = 1.09 \times 10^{-5} M_{\text{dust}} T_{\text{dust}}^6,$$

The monochromatic dust emission flux is expressed as

$$f_{\text{dust}}(\nu) = \kappa_\nu M_{\text{dust}} B_\nu(T_{\text{dust}})/D^2,$$

where $B_\nu$ is the Planck function, $\kappa_\nu$ is the mass absorption coefficient of the dust, and $T_{\text{dust}}$ is the dust temperature. We assume that $\kappa_\nu = 0.7(\nu/340 \text{ GHz})^2 \text{ cm}^2 \text{ g}^{-1}$ (James et al. 2002).

The flux from dust $f_{\text{dust}}(\nu)$ at 880 μm ($\nu = 340$ GHz) used in equation (6) is obtained by subtracting the free–free flux from the total SMA flux as described in Section 2. The values of $f_{\text{dust}}(\nu)$ at 880 μm are listed in Table 2. Considering the errors, the upper/lower value of the free–free contribution and the lower/upper value of the SMA 880 μm flux are used to obtain the lower/upper values of $f_{\text{dust}}$. Equations (5) and (6) indicate that we determine the FIR luminosity so that it is consistent with the observed 880 μm flux as explained at the end of this paragraph (see also Fig. 4 in H11). In H11, we gave $R_{\text{dust}}$ as a free parameter, but in this paper, we determine the typical radius for the distribution of the dust associated with the central star-forming region, to which the SMA data is sensitive. We provide $R_{\text{dust}}$ by the intensity-weighted radius as

$$R_{\text{dust}} = \int \int |r - \bar{r}|^2 I(x, y) \, dx \, dy / \iint I(x, y) \, dx \, dy,$$

where $r = (x, y)$ is the projected position in the image and $\bar{r}$ is the intensity-weighted centre of the image. Although our 880 μm images are contaminated with free–free emission, Beck, Turner, & Gorjian (2001) show similar spatial distributions between mid-infrared dust emission and radio free–free emission in He 2-10, implying that it is reasonable to assume that both dust and free–free have similar spatial extent at 880 μm at least for this

Figure 2. Time evolution of the free–free luminosity at 15 GHz (2 cm) (solid line; left axis for the scale) and the UV luminosity (dashed line; right axis for the scale). Both luminosities are normalized to the stellar mass formed. For age $\lesssim 3$ Myr, the decline of luminosities by stellar death is negligible so that both luminosities normalized to the stellar mass are constant.

non-thermal synchrotron emission or if the age is much older than 3 Myr. In our SMA sample, the contribution from non-thermal emission should be small since the observational spectral indexes at centimetre wavelengths are consistent with thermal free–free (Section 2).

In summary, using $L_\nu (15 \text{ GHz})$ estimated from $f_\nu (15 \text{ GHz})$ in Sections 2.1–2.2 (Table 2), we obtain the stellar mass formed in the current starburst episode ($M_*$) by equation (1). The obtained $M_*$ is used in Section 3.3 to estimate the UV luminosity.

### 3.3 Dust emission

To give a physical interpretation to the dust emission component in the observed 880 μm flux, we need to determine the mass and temperature of the dust. The dust mass (the dust optical depth) and the dust temperature are basic quantities to understand the strength of starburst and the extent of dust enrichment. The total FIR luminosity can also be derived and used to examine the radio–FIR correlation (Section 3.5). We do not directly use optical and UV observations, since they may only trace regions with less extinctions and may not be relevant to what we are modeling (Section 2). We use the same simple model as H11 for the dust emission associated with the central star-forming region in each individual galaxy. Here we summarize the model. At submm wavelengths, the ‘large’ grains, which achieve radiative equilibrium with the ambient stellar radiation field, are the dominant component in the luminosity (e.g. Galliano et al. 2005). For simplicity, we assume that the dust is distributed in a thin shell at a distance $R_{\text{dust}}$ from the centre and that the young stars are located at the centre of the shell (as also assumed in Galliano et al. 2005). The following results are valid as long as the starbursts are more concentrated than the dust distribution. In our sample, the stars associated with the current starburst are more compact than the dust distribution (Gorjian et al. 1993; Johnson et al. 2000; Vanzi et al. 2008). In reality, we should also note that it is difficult to constrain the spatial distribution of stars because of large dust extinctions.

Under the above assumptions, the dust optical depth, $\tau_{\text{dust}}$, for the radiation from stars is estimated as

$$\tau_{\text{dust}} = \frac{3 M_{\text{dust}}}{16 \pi R_{\text{dust}}^2 \alpha_s},$$

where $M_{\text{dust}}$ is the total dust mass in the shell, $\alpha = 0.1 \mu\text{m}$ is the typical grain radius (we adopt the geometrical cross section for the absorption cross section), and $s = 3 \text{ g cm}^{-3}$ is the grain material density (e.g. Draine & Lee 1984).

We assume that the UV luminosity (denoted as $L_{\text{OB}}$) is equal to the bolometric luminosity of the OB stars (stars heavier than 3 $M_\odot$); that is, the total UV luminosity is calculated by summing all the contribution from OB stars under the star formation history and the initial mass function given in Section 3.1. In Fig. 2 we show the evolution of the UV luminosity calculated by the model (see H11 for details). Since Schaerer (2002) does not provide the stellar luminosities for solar metallicity, we adopt the zero-metallicity case. According to Raiter, Schaerer, & Fosbury (2010), the variation of UV luminosity by metallicity under a fixed SFR is negligible so that both luminosities normalized to the stellar mass are consistent with the observed $880 \mu\text{m}$ flux as explained at the end of this paragraph (see also Fig. 4 in H11).
galaxy. For NGC 5253, [Turner & Beck (2004)] show that most of the free–free flux comes from the central 1.2 arcsec region, which implies that dust emission is more extended than free–free emission. In such a case, \( R_{\text{dust}} \) underestimates the actual extension of dust. The value of \( R_{\text{dust}} \) for each galaxy is listed in Table 2. After all, with \( R_{\text{dust}} \) (given in Table 2), \( M_\star \) (derived from the free–free luminosity through equation (1)) and \( L_{\text{FIR}} \) (estimated by equation [3]), the unknown parameters are \( M_{\text{dust}} \) and \( T_{\text{dust}} \) (note that \( \tau_{\text{dust}} \) in equation [5] is given by equation [6]). These two unknowns are obtained by solving equations [5] and [6].

3.4 Derived quantities

The quantities derived by the models above (\( M_\star, M_{\text{dust}}, \) and \( T_{\text{dust}} \)) are listed in Table 2. The stellar mass formed by the current star-burst ranges from a few \( \times 10^6 \) to \( \sim 10^7 \) \( M_\odot \), and the dust mass associated with the star-forming regions is \( \sim 10^3–10^5 \) \( M_\odot \). The solar-metallicity sample, He 2-10, has the largest dust content: if the dust mass is normalized to the stellar mass, its dust-to-stellar mass ratio is \( 4-10 \times 10^{-3} \) in comparison with the values \( 2-3 \times 10^{-3} \) for NGC 5253 and \( <5 \times 10^{-3} \) for II Zw 40. This indicates that He 2-10 is the most dust-enriched system probably because of the highest metallicity. As argued in H11 (see also Section 4.2), the dust is preexisting or grown in dense molecular clouds. Since dust growth is efficient in high-metallicity environments, the highest dust content in the He 2-10 centre among the three sample BCDs can be interpreted to be the consequence of the most efficient dust growth. Dust temperatures (\( \sim 50–60 \) K) higher than those in the Milky Way (\( \sim 15–20 \) K; [Draine & Lee (1984)]) are obtained for all the sample, supporting that intense star formation is occurring in compact regions. Direct constraints on \( T_{\text{dust}} \) from FIR data are crucial in future high-resolution FIR data around the spectral peak, since \( L_{\text{FIR}} \) is the most sensitive to \( T_{\text{dust}} \) than to the other parameters (see equation [5]). However, because \( M_{\text{dust}} \) works as an adjusting factor under a given 880 \( \mu \)m flux through equation [6], the uncertainty in \( L_{\text{FIR}} \) is not so large as expected from the uncertainty in \( T_{\text{dust}} \).

3.5 Radio–FIR relation

In Section 3 we have shown that a large fraction of the SMA 880 \( \mu \)m flux in the sample BCDs is contributed from free–free emission, while the submm emission is usually dominated by dust on global scales of galaxies ([Galliano et al. 2005]). The large contribution from free–free emission to the submm emission may cause a significant impact on the radio–FIR relation in such a way that the radio luminosity is relatively enhanced (H11). Now we examine this issue by plotting the radio–FIR relation for the central regions in our sample BCDs.

In Fig. 3 we show the relation between the monochromatic luminosity at 15 GHz \( L]\,(15 \text{ GHz}) \) and the FIR luminosity \( L_{\text{FIR}} \) for the central star-forming regions in the sample BCDs. \( L_{\text{FIR}} \) has already been obtained in Section 3.2 (see also Table 2). While \( L]\,(15 \text{ GHz}) \) is obtained by using the flux at 15 GHz in Table 2 multiplied by \( 4\pi D^2 \) (see also Sections 2.1, 2.2). The upper and lower bounds of \( L_{\text{FIR}} \) correspond to the lower and upper bounds of \( f_{\text{dust}} \) (the dust flux at 880 \( \mu \)m) given in Table 2. (Recall that \( f_{\text{dust}} \) is the total SMA 880 \( \mu \)m flux minus the free–free contribution. If the free–free contribution were not subtracted, we would overestimate \( L_{\text{FIR}} \) by a factor of 2 or more.) For He 2-10, the upper and lower limits of \( L]\,(15 \text{ GHz}) \) are used, for NGC 5253, we use the measured values, and for II Zw 40, we plot the lower value for \( L]\,(15 \text{ GHz}) \) to put an upper limit for \( L_{\text{FIR}} \) (Fig. 3).

For comparison, we plot the observational data of global emission from BCDs (i.e. the total luminosity from the entire system) in Fig. 5. The sample is taken from Hunt, Bianchi, & Maiolino (2005) for the FIR and 15 GHz global luminosities (squares) and Klein, Weiland, & Brinkl (1991) for the FIR and 10.7 GHz global luminosities (crosses). The 10.7 GHz luminosity is converted to the 15 GHz luminosity by assuming the frequency dependence to be \( \propto \nu^{q(\alpha)} \), where the spectral index \(\alpha\) is given in [Klein et al. (1991)] as a result of fitting to the data at some available radio frequencies (even if we assume \( \langle \alpha \rangle = -0.1 \) for the entire sample, the change of 15 GHz luminosity is too slight to affect our results). As an observational estimate of the FIR luminosity, we adopt an empirically derived formula by Nagata et al. (2002), who estimate the total dust luminosity at \( \lambda \gtrsim 40 \mu \text{m} \) by using the IRAS 60 and 100 \( \mu \)m fluxes.\(^4\) The data are summarized in Appendix A.

We adopt the radio-to-FIR ratio as usually used (e.g. Condon 1992). Here we define \( q_{\text{15}} \) as

\[
q_{\text{15}} = \log \left( \frac{L_{\text{FIR}}}{3.75 \times 10^{12} \text{ W}} \right) - \log \left[ L]\,(15 \text{ GHz}) \right].
\]

The average of \( q_{\text{15}} \) for the global luminosities is \( q_{\text{15}} = 2.80 \) with a standard deviation of 0.34. We show the lines with constant \( q_{\text{15}} \) in Fig. 5. We observe that the data points for the central star-forming regions in our sample are consistent with the range of \( q_{\text{15}} \) (i.e. \( 2.80 \pm 0.34 \)) that explains the global radio–FIR relation of BCDs.

Naively, it would be expected that low-metallicity galaxies have relatively small amount of dust, so that the stellar emission may not be efficiently reprocessed into FIR ([Hirashita & Hunt 1992]). However, [Hirashita & Hunt 2005] show that most of the free–free flux comes from the central 1.2 arcsec region, which implies that dust emission is more extended than free–free emission. In such a case, \( R_{\text{dust}} \) underestimates the actual extension of dust. The value of \( R_{\text{dust}} \) for each galaxy is listed in Table 2. After all, with \( R_{\text{dust}} \) (given in Table 2), \( M_\star \) (derived from the free–free luminosity through equation (1)) and \( L_{\text{FIR}} \) (estimated by equation [3]), the unknown parameters are \( M_{\text{dust}} \) and \( T_{\text{dust}} \) (note that \( \tau_{\text{dust}} \) in equation [5] is given by equation [6]). These two unknowns are obtained by solving equations [5] and [6].

Figure 3. Radio–FIR relation for the central star-forming regions (the diamonds connected by the solid lines for He 2-10 and NGC 5253 and the diamond with an arrow for II Zw 40), in terms of the global relations for BCDs (squares and crosses). The observational data for the global emission from BCDs are taken from Hunt, Bianchi, & Maiolino (2005) (squares) and Klein, Weiland, & Brinkl (1991) (crosses). We also show the solid line with \( q_{\text{15}} = 2.80 \) and the dotted lines with \( q_{\text{15}} = 2.80 \pm 0.34 \) (i.e. \( \pm 1 \sigma \)).

\(^4\) The contribution at 8–40 \( \mu \text{m} \) is neglected since the contribution from these wavelengths to the total FIR is small (at most 30 per cent). The contribution at \( \lambda > 120 \) \( \mu \text{m} \) is included, while it is not included in the FIR luminosity defined by Helou, Soifer, & Rowan-Robinson (1983).
On the other hand, free–free emission does not have such a dependence on metallicity (or dust abundance). Thus, we would expect systematically smaller $q_{12}$ for low-metallicity galaxies. However, NGC 5253 [12 + log(O/H) = 8.14], compared with He 2-10 [12 + log(O/H) = 8.93], does not follow this expectation, which means that even a low metallicity environment can reprocess the stellar light into FIR with a similar efficiency to a solar metallicity environment. As we can see in Table 2, the dust optical depth is comparable between He 2-10 and NGC 5253, although the dust mass is smaller in NGC 5253 than in He 2-10. This is because the distribution of dust is more compact in NGC 5253 than in He 2-10. A compact geometry of dust distribution tends to predict a high dust temperature (e.g. Takeuchi et al. 2005), explaining the observed higher dust temperature in NGC 5253 than in He 2-10. The radio–FIR relation of He 2-10 is still uncertain because of the uncertainty in $L_{\text{FIR}}$. However, it is still possible that this galaxy has a similar $q_{12}$ to the other two galaxies. If its $q_{12}$ is significantly smaller than the other two galaxies, we need to consider the reason other than the metallicity, since NGC 5253, which has a similar metallicity to He 2-10, has a $q_{12}$ value as large as that of a solar metallicity object, He 2-10.

The radio–FIR relation of star-forming dwarf galaxies is similar to that of normal galaxies in spite of the difference in metallicity (Klein et al. 1999, Hopkins, Schulte-Ladbeck, & Drozdovsky 2002, Wu et al. 2008), although some specific galaxies show deviations (Cannon et al. 2006). Thus, metallicity (or dust content) cannot be the dominant factor that governs the radio–FIR relation. Cannon et al. (2008) find a spatial variation of FIR-to-radio ratio by an order of magnitude in a metal poor dwarf galaxy, IC 2574. Dumas et al. (2011) also show different radio–FIR relations between spiral arms and interarm regions in M51. These observations also support the above statement that metallicity is not the dominant factor that varies the FIR-to-radio ratio. The robustness of the FIR-to-radio ratio among our BCD sample is further discussed and interpreted in Section 4.4.

### 3.6 Molecular gas

Gas mass provides the normalization in estimating star formation efficiency and dust-to-gas ratio. The observed wavelength range also covers the CO(3–2) rotational transition line at 345.796 GHz (at rest). Although quite a lot of detections are reported for CO in He 2-10 (e.g. Baas, Israel, & Kooimee 1994, Kobulnicky et al. 1995, Vanzani et al. 2004), we use our data which have the advantage of covering the the same ($u, v$) range. In Table 3 we summarize the quantities derived by our CO(3–2) data.

The spectra around the expected wavelength of CO(3–2) are shown in Fig. 4. The emission is only detected in He 2-10. For II Zw 40, we failed to obtain the data at $> 344.94$ GHz. Yet, we can conclude that CO(3–2) is not detected in this galaxy at the expected frequency.

For He 2-10, we derive the CO(3–2) line flux ($S_{\text{CO}(3-2)}$), the FWHM of the line in units of velocity ($\Delta V$), and the radius of the CO emitting region ($R = 0.7(ab)^{1/2}$, where $a$ and $b$ are respectively the FWHM major and minor axes; Meier et al. 2002). For NGC 5253 and II Zw 40, we derive upper limits for the CO(3–2) line flux. The total mass (dynamical mass) in the central region traced by SMA can be estimated by (MacLaren, Richardson, & Wolfendale 1988, Meier et al. 2002).

$$M_{\text{tot}} = 189 \left( \frac{\Delta V}{\text{km} \, \text{s}^{-1}} \right)^2 \left( \frac{R}{\text{pc}} \right) M_{\odot}. \quad (9)$$

The molecular mass denoted as $M_{\text{mol}}$ is estimated as (Meier et al. 1998).

$$M_{\text{mol}} = 1.23 \times 10^4 \left( \frac{X_{\text{CO}}}{X_{\text{CO}}^{\text{gal}}} \right) \left( \frac{115 \text{ GHz}}{\nu} \right)^2 \left( \frac{D}{1 \text{ Mpc}} \right)^2 \times \left( \frac{S_{\text{CO}(3-2)}}{\text{Jy km s}^{-1}} \right) R_{32/10}^{-2}, \quad (10)$$

where $X_{\text{CO}}^{\text{gal}} = 2.3 \times 10^{20} \text{ cm}^{-2} \text{ (K km s}^{-1})^{-1}$ is the Galactic conversion factor, $X_{\text{CO}}$ is the metallicity-dependent conversion factor (Arimoto, Sofue, & Tsujimoto 1996), and $R_{32/10}$ is the CO(3–2)/CO(1–0) line ratio. We adopt $R_{32/10} = 0.6$ for all the sample as a representative value for dwarf starburst (Meier et al. 2001). The molecular gas mass is compared to the dust mass and the stellar mass to obtain, respectively, the dust-to-gas mass ratio ($M_{\text{mol}} / M_{\text{dust}}$) and $r_s [r_s = M_*/(M_{\text{mol}} + M_*)]$, which under normal conditions (in particular no molecule destruction), provides the star-formation efficiency.

We detected CO(3–2) only in He 2-10, while we obtained only upper limits for NGC 5253 and II Zw 40. Our observations are sensitive only to the centrally concentrated component. Diffuse components, if any, may be resolved out. Table 3 indicates that ($M_{\text{mol}}, M_{\text{tot}}$) = (9.4 x $10^7 M_\odot$, 1.0 x $10^9 M_\odot$) for the central star-forming region of He 2-10 with $\Delta V = 40.8$ km s$^{-1}$. Vanzani et al. (2004) reported $\Delta V = 53$ km s$^{-1}$ for the central 20 arcsec in He 2-10. Meier et al. (2001) estimate ($M_{\text{mol}}, M_{\text{tot}}$) = (1.4 x $10^8 M_\odot$, 3.3 x $10^8 M_\odot$) and (3.7 x $10^7 M_\odot$, 9.4 x $10^7 M_\odot$) for He 2-10 and NGC 5253, respectively. Their large velocities and masses are due to different spatial scales traced. No CO(3–2) detection has been reported for II Zw 40, but the molecular mass derived from CO(2–1) and CO(1–0) (< 5 x $10^6 M_\odot$) is not contradictory with our upper limit.

In the He 2-10 centre, $M_{\text{tot}} \approx M_{\text{mol}}$, and the stellar mass only occupies a small fraction (~ 10 per cent) of the total mass. A star formation efficiency of ~ 10 per cent is near the values derived for the Galactic giant molecular clouds (Lada, Lombardi, & Alves).
The dust-to-gas ratio is significantly smaller than the Galactic value ($\sim 6 \times 10^{-3}$, Spitzer 1978), although the metallicity is similar. This is probably because we only trace the high-temperature dust component that is directly heated by the current starburst without being shielded by other dust components. A similar underestimate of dust mass is also reported by Sun & Hirashita (2011). Thus, we may miss a large amount of dust if a small amount of dust efficiently shields the stellar light.

For the low-metallicity objects, NGC 5253 and II Zw 40, the upper limits of molecular gas mass can be used to constrain the lower limits for $\epsilon_*$ and $\mathcal{D}$. Both objects have significantly larger $\epsilon_*$ than He 2-10. This is interpreted in two ways: (i) the star formation efficiency is actually high, or (ii) molecular gas is dissociated quickly ($<3$ Myr), causing an underestimate of the total gas mass. These two possibilities are further discussed in Section 4.3.

### 4 DISCUSSION

#### 4.1 Free–free contribution at 880 μm

In H11, the 880 μm luminosity in the IW Zw 40 centre is shown to be dominated by free–free emission. This is why H11 suggests that free–free dominated emission at $<880$ μm can be used to select extremely young starbursts ($<3$ Myr). In this paper, this is confirmed in the sense that the central star-forming regions in He 2-10 and NGC 5253 also have significant contributions of free–free emission at 880 μm (Section 3.1). There is a hint in Table 1 that metallicity becomes higher the free–free fraction becomes lower (i.e. the fraction of dust emission becomes higher). This trend should be checked with a larger sample in the future.

Although free–free emission has a significant contribution even at 880 μm (while global 880 μm emission (‘global’ refers to the integrated emission of the entire galaxy) is generally dominated by dust (e.g. Hunt et al. 2005), the radio–FIR relation of the central regions in our sample BCDs is surprisingly consistent with that defined by using global luminosities as shown in Fig. 3. This is probably due to the high dust temperatures, which enhance the FIR luminosity and compensates the small contribution from free emission at 880 μm. Therefore, it is possible that this compensating effect is a key to understand the robustness of the radio–FIR relation.

The robustness of the radio–FIR relation may simply reflect the fact that both radio and FIR luminosities are good indicators of star formation activities (Condon 1992). If we assume the robustness of the radio–FIR relation, we can explain the small contribution of dust emission at 880 μm in comparison with free–free emission as follows. By assumption, the free–free flux at 880 μm ($f_{\text{ff}}(\nu)$) is just proportional to the total FIR flux, which is proportional to $T_{\text{dust}}^3$ (for dust mass absorption coefficient $\propto \nu^2$; Draine & Lee 1984). On the other hand, if the Rayleigh–Jeans approximation is valid, the 880 μm dust flux, $f_{\text{dust}}(\nu)$, is proportional to $T_{\text{dust}}^4$. Therefore, $f_{\text{ff}}(\nu)/f_{\text{dust}}(\nu) \propto T_{\text{dust}}$, which indicates that the fraction of free–free emission at 880 μm is larger for a higher dust temperature.

To examine this temperature dependence of the free–free fraction, we plot $f_{\text{ff}}(\nu)/f_{\text{dust}}(\nu)$ at 880 μm in terms of $T_{\text{dust}}$ for the global emission in the BCDs which were used to plot the radio–FIR relation in Fig. 3 (i.e. the samples taken from Hunt et al. 2005; Klein et al. 1991). For these BCDs, we estimate $f_{\text{dust}}$ at 880 μm as described in Appendix A. The free–free flux at 880 μm ($f_{\text{ff}}$) is estimated by converting the free–free flux at 15 GHz used in Fig. 5 to that at 880 μm by assuming a frequency dependence of $\nu^{-0.1}$. We also plot our SMA sample for the central parts in BCDs. We find that there is a positive trend of $f_{\text{ff}}/f_{\text{dust}}$ with $T_{\text{dust}}$ as expected above. We also draw a line with $f_{\text{ff}}/f_{\text{dust}} \propto T_{\text{dust}}$ with an arbitrary normalization in Fig. 5. This line roughly bridges our sample and the above samples, although the large scatter of the data implies that our discussion may be too simplified. Supported by the correlation between $f_{\text{ff}}/f_{\text{dust}}$ and $T_{\text{dust}}$, we conclude that the large contribution of free–free emission in our observation is a natural consequence of picking up active star-forming regions which have high dust temperatures.

The large free–free fraction in the central star-forming regions of our sample indicates that the subtraction of free–free emission at submillimetre wavelengths is a critical step in studying the dust emission. Galliano et al. (2005) find that the submm excess in some BCDs needs to be fitted with ‘very cold grains’, whose derived abundance may be sensitive to the subtraction of free–free emission. Submm excess is preferentially seen in low-metallicity dwarf galaxies (Galametz et al. 2011). Since we have assumed that the SMA 880 μm flux is dominated by the warm dust component heated by young stars, we cannot test the existence of this very cold component in the central star-forming regions. We need to wait for multi-wavelength observations at FIR–submm wavelengths with spatial resolutions of a few arcsec to tackle this issue.

#### 4.2 Dust abundance

As mentioned in Section 3.4, the dust-to-stellar mass ratio is larger in He 2-10 than in the other two galaxies, while as shown in Section 3.5, the dust-to-molecular gas mass ratio does not necessarily trace the trend of metallicity. The dust-to-gas ratio derived for He 2-10 is much lower than the Galactic dust-to-gas ratio ($6 \times 10^{-3}$; Spitzer 1978), although He 2-10 is a solar-metallicity object. As interpreted in Section 3.5, the dust mass in He 2-10 may be underestimated because we only trace the dust directly heated by the central star clusters; that is, the dust mass estimate from dust emission is not sensitive to the dust in regions where the UV radiation from the central stars is shielded.

As argued in H11, the observed dust should either be pre-existing or have grown by accretion in the dense star-forming regions. According to Hirashita & Kuo (2011) (see also Hunt et al. 2011).
Figure 4. Spectra around the frequency where the CO(3–2) line is expected. Panels (a), (b), and (c) show the spectrum in the central part of He 2-10, NGC 5253, and II Zw 40, respectively. The LSR velocity is also shown on the upper axis. For the latter two galaxies, we did not detect significant CO(3–2) emission, whose expected frequency is marked by the arrow.

Figure 5. Relation between the free–free-to-dust flux ratio estimated at 880 $\mu$m and the dust temperature. He 2-10, II Zw 40, and NGC 5253, in terms of the global relations for BCDs. The observational data for the global emission of BCDs are taken from Hunt et al. (2005) and Klein et al. (1991) for squares and crosses, respectively. We also show the relation with $f_{\text{ff}}/f_{\text{dust}} \propto C T_{\text{dust}}^5$, where a constant $C$ is chosen arbitrarily.

Asano et al. (2012), the dust-growth time-scale for silicate (a similar time-scale is obtained for carbonaceous dust) is estimated as

$$
\tau_{\text{grow}} \approx 2.1 \times 10^5 \, \text{yr} \left( \frac{\langle a^3 \rangle}{\langle a^2 \rangle} \right) \left( \frac{Z}{1 \, \text{Z}_\odot} \right)^{-1} \times \left( \frac{n_\text{H}}{10^8 \, \text{cm}^{-3}} \right)^{-1} \left( \frac{T_{\text{gas}}}{50 \, \text{K}} \right)^{-1/2} \left( \frac{S}{0.3} \right)^{-1},
$$

where $\langle a^3 \rangle$ and $\langle a^2 \rangle$ are the averages of $a^3$ and $a^2$ ($a$ is the grain radius) for the grain size distribution (we adopt $\langle a^3 \rangle/\langle a^2 \rangle = 0.1 \, \mu$m), $Z$ is the metallicity (we adopt $Z = 1.75, 0.28$, and $0.28 \, \text{Z}_\odot$ for He 2-10, NGC 5253, and II Zw 40, respectively, by assuming that the solar oxygen abundance is $12+\log(O/H) = 8.69$; Lodders 2003), $n_\text{H}$ is the hydrogen number density (we adopt $n_\text{H} = 10^5$ cm$^{-3}$ for the dense star-forming regions in BCDs; H11), $T_{\text{gas}}$ is the gas temperature (we adopt $T_{\text{gas}} = 50$ K; Wilson, Walker, & Thornley 1997) and $S$ is the sticking efficiency of the relevant metal species onto the dust surface (we adopt $S = 0.3$; Leitch-Devlin & Williams 1985; Grassi et al. 2011). Then, we obtain $\tau_{\text{grow}} \sim 0.12, 0.75$ and 0.75 Myr for He 2-10, NGC 5253, and II Zw 40, respectively. These time-scales are shorter than or comparable to the ages of the star-forming regions ($\lesssim$ a few Myr).

Therefore, dust growth by the accretion of gas-phase metals can be an effective mechanism of increasing the dust content in the central star-forming regions of those BCDs.

4.3 Molecular gas properties

In Section 3.6, we have shown that the evaluated star formation efficiencies in the central parts of the low-metallicity BCDs (NGC 5253 and II Zw 40) are high. Such high star formation efficiencies in low-metallicity galaxies are already reported when CO emission is used for the molecular gas tracer (e.g. Schruba et al. 2012). However, no physical mechanism that makes the star formation in metal-poor gas efficient is known. Hirashita & Ferrara (2002) suggest that star formation is rather inefficient in low metallicity (i.e. low dust-to-gas ra-
Figure 6. Relation between FIR luminosity and CO(3–2) luminosity for the central part of He 2-10, NGC 5253, and II Zw 40. We also show the linear fitting relation in Meier et al. (2001) applicable for dwarf galaxies (solid line) and for non-dwarf galaxies (dotted line; originally derived from Mauersberger et al. 1999). The dashed lines show the typical scatter for the dwarf sample in Meier et al. (2001).

Figure 6. As a reference, we also show the global (i.e. entire galaxy) correlation between CO and FIR luminosity for non-dwarf galaxies (mostly spiral galaxies). Such a correlation between CO and FIR luminosity has been well investigated (e.g. Gao & Solomon 2003). The relation for the dwarf sample (solid line) is systematically deviated. The deviation is even larger if we focus on the central part of NGC 5253. It is probably because we pick up a region with an intense radiation field (i.e., strong CO dissociation) if we pick up the central region.

4.4 Implication for high-redshift observations

High-redshift starbursts are often traced by observations of dust continuum and/or CO (e.g. Michałowski et al. 2010). BCDs, which host compact star-forming regions with various evolutionary stages (i.e. various metallicities), provide good ‘laboratories’ of high-z galaxies (or galaxy evolution), although our sample size is still limited. For the He 2-10 centre, the gas mass derived from the CO observation through a conventional conversion factor matches the total dynamical mass for the He 2-10 centre, supporting that CO is a good tracer of the total gas mass in this particular BCD. However, as discussed in Section 3.6, large values of star formation efficiency in low-metallicity BCDs, NGC 5253 and II Zw 40, imply that CO luminosity is not necessarily a good indicator of the total gas mass in low-metallicity starburst environments. Thus, if a high-z galaxy has a metallicity significantly lower than solar, CO luminosity has the risk of underestimating the total gas mass.

This underestimate of gas mass propagates to the estimate of dust-to-gas ratio. Moreover, there is a potential risk of underestimating dust mass because we may miss low-temperature dust components, which are less luminous than high-temperature components directly heated by the current starbursts (Section 4.2). Thus, as long as we trace the dust content by emission and the gas content by CO lines, there is a possibility that the obtained dust-to-gas ratio is not reliable.

For the origin of dust, it is suggested that dust growth is the most efficient mechanism of dust production in high-redshift starbursts (Mattsson 2011; Valiante et al. 2011). As suggested in our BCD observations (Section 4.3), high gas densities in intense starbursts make the grain growth time-scale short.

5 CONCLUSION

In order to reveal the submm–radio radiative properties of young active starbursts in BCDs, the central star-forming regions in He 2-10, NGC 5253, and II Zw 40 were observed in the 340 GHz (880 μm) band at ~ 5″ resolution with SMA. The 880 μm fluxes have been decomposed into free–free and dust emission components by using centimetre radio data in the literature. At 880 μm, free–free emission has proven to have a contribution comparable to or larger than dust emission in the central part of all the three BCDs. We have also shown that the fraction of free–free emission at 880 μm has a positive correlation with the dust temperature. In spite of the dominance of free–free emission at 880 μm, the radio–FIR relation of the central parts in the BCDs is consistent with the relation defined for the global luminosities (i.e. the luminosities in the entire system), supporting the robustness of the radio–FIR correlation. Finally, we have analyzed the CO(3–2) emission line, finding that CO is a good tracer of the total gas mass in He 2-10, while CO is deficient in the low-metallicity BCDs (NGC 5253 and II Zw 40), probably due to inefficient shielding of dissociating photons in dust-poor environments. We also point out that the dust mass may be potentially underestimated since emission is always biased to the dust directly heated by the stars. Thus, we should keep in mind these potential underestimates of gas and dust masses in interpreting submm observations of not only nearby galaxies but also high-redshift galaxies.
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APPENDIX A: DATA FOR THE RADIO–FIR RELATION

We collected radio fluxes around 2 cm (15 GHz) and FIR (IRAS 60 and 100 $\mu$m) fluxes of BCDs in the literature. We adopt Hunt et al. (2005) and Klein et al. (1991) (Tables A1 and A2, respectively). The flux listed in these two tables is a global flux (i.e. flux from the entire galaxy). For the radio fluxes in Hunt et al. (2005), if more than two data are available at the same wavelength, we adopt the data in the lowest-resolution mode, which is expected to have the smallest missing flux. We select BCDs with detections both at IRAS 60 and 100 $\mu$m, and at 2 cm (15 GHz). For Klein et al. (1991)'s sample, we adopt the Effelsberg 2.8 cm flux and convert it to the 2 cm flux by adopting average radio spectral indices $\langle \alpha \rangle$ given in Table 6 of Klein et al. (1991). We exclude BCDs without detection by IRAS. The IRAS fluxes of Klein et al. (1991)'s samples are taken from Moshir et al. (1990).

For these samples, we need to estimate dust temperatures and fluxes at 880 $\mu$m in Fig. 5. We adopt the following estimator, $T_{L_G2}$, for the dust temperature (Nagata et al. 2002):

$$T_{L_G2} = 11.8 \frac{f_{\nu}(100 \mu m)}{f_{\nu}(60 \mu m)} + 13.8 \,[K].$$  \hspace{1cm} (A1)

We use this dust temperature for $T_{\text{dust}}$ in the text. By using $T_{L_G2}$, the dust flux at 880 $\mu$m is estimated as

$$f_{\text{dust}}(\nu)\big|_{880 \mu m} = \left( \frac{100}{880} \right)^5 \frac{\exp(143.9/T_{L_G2}) - 1}{\exp(16.35/T_{L_G2}) - 1} \times f_{\nu}(100 \mu m).$$  \hspace{1cm} (A2)

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nearby sources, we replaced the value with an interferometric flux at 2 cm (15 GHz) given by

| Galaxy     | \( f_v \) (2 cm) (mJy) | \( f_v \) (60 \( \mu \)m) (Jy) | \( f_v \) (100 \( \mu \)m) (Jy) | \( D \) (Mpc) |
|------------|------------------------|-------------------------------|-------------------------------|--------------|
| He 2-10    | 21.1 ± 1.2             | 24.1 ± 2.4                    | 26.4 ± 2.6                    | 10.5         |
| NGC 5253   | 54 ± 5                 | 30.5 ± 1.2                    | 29.4 ± 1.8                    | 3.7          |
| II Zw 40   | 12 ± 3                 | 6.61 ± 0.70                   | 5.80 ± 0.90                   | 10.5         |
| Mrk 33     | 16.0 ± 0.06            | 4.77 ± 0.04                   | 5.99 ± 0.13                   | 24.9\(^a\)   |

\(^a\) Tully (1988).

Table A2. **Klein et al. (1993)**’s sample for the radio–FIR relation.

| Galaxy\(^a\) | \( f_v \) (2.8 cm) (mJy) | \( \langle \alpha \rangle \) | \( f_v \) (60 \( \mu \)m) (Jy) | \( f_v \) (100 \( \mu \)m) (Jy) | \( D \) (Mpc) |
|------------|------------------------|----------------|-------------------------------|-------------------------------|--------------|
| Haro 14    | 2.4 ± 0.8              | −0.51 ± 0.18\(^b\) | 0.530 ± 0.069                 | 1.04 ± 0.14                   | 13.9         |
| Haro 15    | 6.6 ± 0.5              | −0.83 ± 0.21       | 1.35 ± 0.12                   | 1.97 ± 0.20                   | 95.4         |
| Mrk 370    | 2.7 ± 0.7              | −0.44 ± 0.11       | 1.21 ± 0.11                   | 3.03 ± 0.24                   | 12.9         |
| II Zw 40   | 21 ± 2                 | −0.20 ± 0.05       | 6.61 ± 0.70                   | 5.80 ± 0.90                   | 10.5         |
| Haro 1     | 21 ± 3                 | −0.48 ± 0.08       | 8.57 ± 0.43                   | 12.9 ± 0.65                   | 52.0         |
| Mrk 86     | 7.4 ± 2.0              | −0.30 ± 0.45       | 3.24 ± 0.19                   | 6.45 ± 0.39                   | 7.0          |
| Mrk 401    | 11 ± 4                 | −0.51 ± 0.18\(^b\) | 2.57 ± 0.13                   | 4.01 ± 0.24                   | 22.2         |
| Haro 23    | 5.5 ± 0.8              | +0.71 ± 0.30       | 0.401 ± 0.044                 | 0.778 ± 0.132                 | 17.4         |
| Mrk 140    | 18 ± 6                 | −0.29 ± 0.04       | 0.370 ± 0.041                 | 0.630 ± 0.126                 | 22.7         |
| Haro 2     | 7.1 ± 0.9              | −0.59 ± 0.10       | 4.68 ± 0.28                   | 5.32 ± 0.32                   | 20.5         |
| Haro 3     | 9.1 ± 2.0              | −0.25 ± 0.02       | 4.95 ± 0.40                   | 6.75 ± 0.41                   | 13.9         |
| Mrk 186    | 7 ± 3                  | +0.44 ± 0.54       | 1.09 ± 0.066                  | 2.52 ± 0.123                  | 11.1         |
| Mrk 169    | 8 ± 2                  | −0.49 ± 0.07       | 3.17 ± 0.29                   | 4.79 ± 0.29                   | 17.4         |
| Haro 28    | 1.5 ± 0.7              | −1.11 ± 0.60       | 1.09 ± 0.08                   | 2.29 ± 0.23                   | 10.7         |
| Mrk 49     | 4.5 ± 1.5              | −0.46 ± 0.52       | 0.724 ± 0.065                 | 0.823 ± 0.140                 | 18.2         |
| Haro 9     | 17 ± 5                 | +0.33 ± 0.41       | 2.63 ± 0.21                   | 4.47 ± 0.27                   | 13.9         |
| Mrk 59     | 6.1 ± 1.3              | −0.43 ± 0.09       | 1.97 ± 0.12                   | 2.46 ± 0.20                   | 11.6         |
| II Zw 70   | 4.4 ± 1.0              | −0.26 ± 0.06       | 0.714 ± 0.050                 | 1.24 ± 0.12                   | 17.1         |
| Mrk 297    | 22 ± 5                 | −0.81 ± 0.09       | 6.15 ± 0.31                   | 10.2 ± 0.5                   | 63.0         |
| Mrk 313    | 7.5 ± 0.5              | −0.63 ± 0.13       | 3.80 ± 0.30                   | 7.40 ± 0.59                   | 30.8         |
| Mrk 314    | 3.9 ± 0.7\(^c\)       | —                  | 1.25 ± 0.10                   | 1.49 ± 0.37                   | 31.1         |
| III Zw 102 | 16.7 ± 1.0             | −0.62 ± 0.01       | 9.33 ± 0.56                   | 17.8 ± 1.1                   | 25.0         |

\(^a\) II Zw 40 and Haro 2 (= Mrk 33) are also included in **Hunt et al. (2005)**’s sample (Table A1).
\(^b\) Since \( \langle \alpha \rangle \) is not available, we assume the mean value obtained in **Klein et al. (1991)**.
\(^c\) Since the flux given by **Klein et al. (1991)** is probably overestimated because of confusion with nearby sources, we replaced the value with an interferometric flux at 2 cm (15 GHz) given by Deeg, Duric, & Brinks (1997).

Note: Mrk 527 was originally included in the sample of **Klein et al. (1991)**. Because of the suspected contamination of nearby sources, this galaxy is not included in our sample.