

DETECTION OF THE 158 μm [C II] TRANSITION AT $z = 1.3$: EVIDENCE FOR A GALAXY-WIDE STARBURST

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ABSTRACT

We report the detection of 158 μm [C II] fine-structure line emission from MIPS J142824.0+352619, a hyperluminous ($L_{\text{IR}} \sim 10^{13} L_{\odot}$) starburst galaxy at $z = 1.3$. The line is bright, corresponding to a fraction $L_{[\text{C II}]} / L_{\text{FIR}} \approx 2 \times 10^{-3}$ of the far-IR (FIR) continuum. The [C II], CO, and FIR continuum emission may be modeled as arising from photodissociation regions (PDRs) that have a characteristic gas density of $n \sim 10^{4.2} \text{ cm}^{-3}$, and that are illuminated by a far-UV radiation field $\sim 10^{3.2}$ times more intense than the local interstellar radiation field. The mass in these PDRs accounts for approximately half of the molecular gas mass in this galaxy. The $L_{[\text{C II}]} / L_{\text{FIR}}$ ratio is higher than observed in local ultraluminous infrared galaxies or in the few high-redshift QSOs detected in [C II], but the $L_{[\text{C II}]} / L_{\text{FIR}}$ and $L_{\text{CO}} / L_{\text{FIR}}$ ratios are similar to the values seen in nearby starburst galaxies. This suggests that MIPS J142824.0+352619 is a scaled-up version of a starburst nucleus, with the burst extended over several kiloparsecs.

Key words: galaxies: high-redshift – galaxies: individual (MIPS J142824.0+352619) – galaxies: ISM – galaxies: starburst – infrared: galaxies – submillimeter: general

Online-only material: color figures

1. INTRODUCTION

The $^2P_{3/2} \rightarrow ^2P_{1/2}$ transition of C^+ ($\lambda = 157.74 \mu\text{m}$) is one of the brightest emission lines in star-forming galaxies, typically accounting for 0.1%–1% of the far-IR (FIR) continuum (Stacey et al. 1991; Malhotra et al. 2001). Much of this emission arises from the warm and dense photodissociation regions (PDRs) that form on the UV-illuminated surfaces of molecular clouds. The [C II] transition is a primary PDR coolant, and is a sensitive probe of both the physical conditions of the photodissociated gas and the intensity of the ambient stellar radiation fields (Hollenbach & Tielens 1999). In ultraluminous infrared galaxies (ULIRGs), the $L_{[\text{C II}]} / L_{\text{FIR}}$ ratio is a factor of ~ 7 times lower than in less luminous systems (Luhman et al. 2003), for reasons that are not well understood.

Large-aperture (sub)millimeter telescopes have been used to search for [C II] emission from sources at $z > 3$, and three FIR-luminous QSOs at $z = 4.4$ – 6.4 have been detected thus far. SDSS J1148 (Maiolino et al. 2005) and BR 1202N (Iono et al. 2006c) have low $L_{[\text{C II}]} / L_{\text{FIR}}$ ratios similar to or smaller than the mean local ULIRG value, while BRI 0952 (Maiolino et al. 2009) has a somewhat larger ratio falling at the lower end of the range seen in normal galaxies. We have initiated a search for [C II] emission from galaxies at $z = 1$ – 2 , concentrating on star-formation-dominated systems selected by their FIR or submillimeter continuum brightness. Here, we report our first detection, from the $z = 1.3$ hyperluminous starburst galaxy MIPS J142824.0+352619 (hereafter MIPS J1428).

MIPS J1428 was identified in a *Spitzer*/MIPS blank field survey as a bright 160 μm source with red optical/near-IR colors,

and subsequent spectroscopic and photometric measurements established it as a hyperluminous ($L_{\text{IR}}[8\text{--}1000 \mu\text{m}] = 3.2 \times 10^{13} L_{\odot}$) galaxy at $z = 1.325$ (Borys et al. 2006). There are several indications that this IR emission is powered by star formation, including the brightness of the polycyclic aromatic hydrocarbon (PAH) features and the nondetection in hard X-ray emission. With a starburst origin the estimated L_{IR} corresponds to a star formation rate of $\sim 5500 M_{\odot} \text{ yr}^{-1}$ (Borys et al. 2006; Desai et al. 2006). MIPS J1428 was detected in CO(2 \rightarrow 1) and CO(3 \rightarrow 2), and the line luminosities correspond to a large gas mass of $M_{\text{H}_2} \sim 10^{11} M_{\odot}$ (Iono et al. 2006b). However, a gravitational lens may amplify the flux by as much as a factor of 10 (Borys et al. 2006; Iono et al. 2006a, 2006b), making the actual star formation rate and gas mass correspondingly lower. Independent of the unknown lensing amplification, the large value of $L_{\text{IR}} / L'_{\text{CO}} \approx 320 L_{\odot} (\text{K km s}^{-1})^{-1}$ (Iono et al. 2006b) indicates that MIPS J1428 is forming stars with high efficiency, similar to that seen in local ULIRGs and high-redshift submillimeter galaxies (SMGs; Solomon & Vanden Bout 2005).

This is the first detection of [C II] in the $z = 1$ – 3 epoch of peak star formation activity in the universe and the first detection from a high-redshift galaxy not associated with a QSO.

2. OBSERVATIONS

We observed the [C II] line toward MIPS J1428 in 2008 March with ZEUS (Stacey et al. 2007; Hailey-Dunsheath 2009) at the Caltech Submillimeter Observatory (CSO)⁸ on Mauna Kea, Hawaii. ZEUS is a dual-band (350 and 450 μm) grating spectrometer equipped with a 1×32 semiconductor bolometer array. For this observing run, the instrument was configured as described in Hailey-Dunsheath et al. (2008). At

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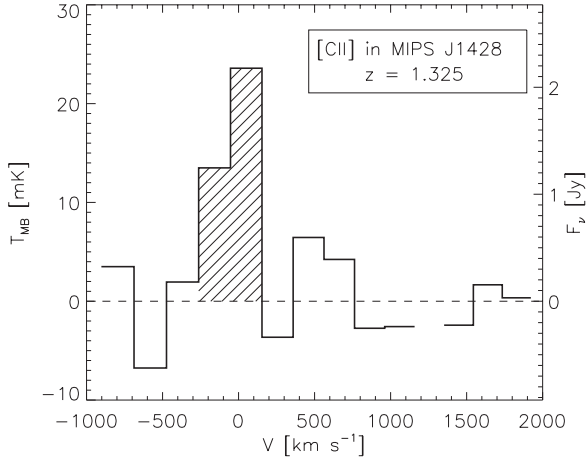


Figure 1. ZEUS/CSO spectrum of the $158\ \mu\text{m}$ [C II] transition in MIPS J1428. The velocity scale is referenced to $z = 1.325$, and the pixel centered at $v = 1250\ \text{km s}^{-1}$ is removed due to the presence of a telluric absorption feature. The integrated intensity is obtained by summing the two central spectral bins, which cover $\Delta v = 416\ \text{km s}^{-1}$. The line is detected at 6σ significance.

the redshifted wavelength ($\lambda = 366.75\ \mu\text{m}$) of the [C II] transition, the spectrometer provides a slit-limited resolving power of $\lambda/\Delta\lambda \approx 900$, and the 14 detectors operating in the $350\ \mu\text{m}$ window combine to provide an instantaneous bandwidth corresponding to $\delta v = 2825\ \text{km s}^{-1}$.

Orion (BN-KL) was used as a spectral calibrator and Mars ($T_B = 213\ \text{K}$; Hildebrand et al. 1985) as a flux calibrator. We integrated on MIPS J1428 for a total of 135 minutes (including chopping) in good submillimeter weather, with $\tau_{350\ \mu\text{m}} = 1.0\text{--}1.5$. The $13''$ ZEUS/CSO beam was centered at R.A. = $14^{\text{h}}28^{\text{m}}24^{\text{s}}.1$, decl. = $+35^{\circ}26'19''$ (J2000.0), and the data were obtained by chopping and nodding the telescope with a $30''$ throw. A linear baseline is removed from the final spectrum, shown in Figure 1. The integrated line flux is $F_v\Delta v = 713\ \text{Jy km s}^{-1}$, and we compare this with other observations in Table 1. With $L_{\text{FIR}} = 2.6 \times 10^{13}\ L_{\odot}$ (Borys et al. 2006), we estimate $L_{[\text{C II}]} / L_{\text{FIR}} \approx 2.1 \times 10^{-3}$.

3. RESULTS

3.1. Origins of the [C II] Line

Carbon has a lower ionization potential (11.26 eV) than hydrogen and consequently the [C II] transition is an important coolant of both ionized gas and diffuse atomic gas. However, most of the [C II] emission from nearby IR-bright galaxies arises from dense PDRs illuminated by the far-UV (FUV) radiation from young stars (Crawford et al. 1985; Stacey et al. 1991). Combined H II region and PDR modeling of the starburst templates NGC 253 (Carral et al. 1994) and M82 (Lord et al. 1996; Colbert et al. 1999) has demonstrated that PDRs account for at least 70% of the [C II] emission in these sources. The available data suggest that such starburst galaxies are the best local analogs of MIPS J1428 (see Section 4), so here we assume that 70% of the [C II] emission from MIPS J1428 arises in PDRs. We further assume that PDRs produce all of the CO(2→1), CO(3→2), and FIR continuum emission in this source, and we model these tracers as arising from a single representative PDR.

3.2. PDR Analysis

We use the PDR models of Kaufman et al. (1999) in which the emission is determined by the gas density, n , and the incident

Table 1
Spectral Line and Continuum Observations of MIPS J1428

Tracer	Flux (Jy km s ⁻¹)	L (L_{\odot})	σ (%)	Reference
[C II]	713	5.4×10^{10}	30	1
CO(2→1)	5.3	4.9×10^7	23	2
CO(3→2)	13.9	1.9×10^8	35	2
IR (8–1000 μm)	...	3.2×10^{13}	22	3
FIR ^a	...	2.6×10^{13}	22	3

Notes. Luminosities are uncorrected for lensing and are calculated using $\Omega_M = 0.27$, $\Omega_{\Lambda} = 0.73$, $H_0 = 71\ \text{km s}^{-1}\ \text{Mpc}^{-1}$.

^a We estimate the rest-frame $60\ \mu\text{m}$ and $100\ \mu\text{m}$ luminosity densities from the Borys et al. (2006) model spectral energy distribution (SED) and calculate L_{FIR} following $F_{\text{FIR}} = 1.26 \times 10^{-14} (2.58 f_{60} + f_{100})\ \text{W m}^{-2}$ (Sanders & Mirabel 1996).

References. (1) This work; (2) Iono et al. 2006b; (3) Borys et al. 2006.

FUV ($6\ \text{eV} < h\nu < 13.6\ \text{eV}$) flux, G_0 (expressed in units of the Habing Field, $1.6 \times 10^{-3}\ \text{erg cm}^{-2}\ \text{s}^{-1}$). These models calculate the line emission generated by a cloud illuminated on only one side and must be modified to model clouds in the active regions of galaxies that are illuminated on all sides. For this geometry, Kaufman et al. (1999) note that an observer will detect optically thin radiation emitted by both the near and far sides of the cloud, while optically thick emission will only be visible from the near side. The [C II] line is generally moderately optically thin in these calculations, and the FIR continuum is also assumed to be optically thin, but the low- J CO transitions are optically thick for the nominal $A_V = 10$ cloud depth. We therefore increase the measured CO fluxes by a factor of 2 with respect to these other tracers before comparing with the models.

In Figure 2, we show the values of n and G_0 allowed by the observations listed in Table 1, after correcting the [C II] and CO measurements as described above. In the $n \approx 10^3\text{--}10^5\ \text{cm}^{-3}$ range, the $L_{[\text{C II}]} / L_{\text{FIR}}$ ratio provides a strong constraint on G_0 , while the $L_{[\text{C II}]} / L_{\text{CO}(2\rightarrow1)}$ ratio is primarily a function of density. The best-fit solution obtained from these two ratios is consistent with the $n \gtrsim 10^{3.5}\ \text{cm}^{-3}$ lower limit imposed by the $L_{\text{CO}(3\rightarrow2)} / L_{\text{CO}(2\rightarrow1)}$ ratio, and we conclude that the relative strengths of the [C II], CO(2→1), CO(3→2), and FIR continuum emission may be reproduced by a PDR with $n \sim 10^{4.2}\ \text{cm}^{-3}$ and $G_0 \sim 10^{3.2}$. Reducing the PDR contribution to the total [C II] emission by a factor of 2 (3) would increase n by a factor of 7.2 (22), but G_0 by only a factor of 1.6 (1.8). We also note that without the factor of 2 correction to the observed CO fluxes, n would be 4.2 times lower, but G_0 would remain unchanged.

An estimate of the atomic gas mass associated with the PDRs in MIPS J1428 is obtained from the inferred [C II] luminosity and this PDR solution. Assuming the [C II] emission is optically thin, this mass is given as

$$\frac{M_a}{M_{\odot}} = 0.77 \left(\frac{0.7 L_{[\text{C II}]}}{L_{\odot}} \right) \left(\frac{1.4 \times 10^{-4}}{X_{\text{C}^+}} \right) \times \frac{1 + 2 \exp(-91\ \text{K}/T) + n_{\text{crit}}/n}{2 \exp(-91\ \text{K}/T)}, \quad (1)$$

where we use a C^+ abundance per hydrogen atom of $X_{\text{C}^+} = 1.4 \times 10^{-4}$ (Savage & Sembach 1996). The surface temperature of a PDR with $n = 10^{4.2}\ \text{cm}^{-3}$ and $G_0 = 10^{3.2}$ is $T_s \approx 230\ \text{K}$ (Kaufman et al. 1999). Assuming this temperature is

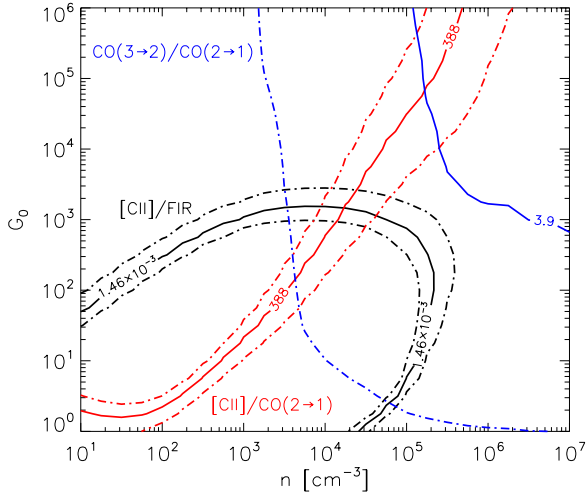


Figure 2. $L_{[\text{CII}]} / L_{\text{FIR}}$, $L_{[\text{CII}]} / L_{\text{CO}(2 \rightarrow 1)}$, and $L_{\text{CO}(3 \rightarrow 2)} / L_{\text{CO}(2 \rightarrow 1)}$ as a function of density (n) and FUV flux (G_0), from the PDR models of Kaufman et al. (1999). Contours are drawn for the measured values (solid) and $\pm 1\sigma$ uncertainties (dot-dashed) of MIPS J1428, after scaling the $[\text{CII}]$ flux by 70% to account for a non-PDR contribution and increasing the CO fluxes by a factor of 2 to account for geometrical effects (see Section 3).

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representative of the full C^+ region and adopting a critical density of $n_{\text{crit}} = 2.7 \times 10^3 \text{ cm}^{-3}$ (Launay & Roueff 1977), this expression yields $M_a = 5.5 \times 10^{10} \mu^{-1} M_\odot$ (where μ is the lensing amplification). This is 55% of the molecular gas mass estimated from the CO luminosity (Iono et al. 2006b), which is similar to the PDR mass fractions in starburst galaxies (Stacey et al. 1991, corrected for the smaller X_{C^+} used here). Much like in nearby starburst nuclei, the PDR mass in MIPS J1428 is a significant fraction of the total molecular gas mass.

4. DISCUSSION

4.1. $[\text{CII}]$, CO, and the FIR Continuum: A Comparison to Other Galaxies

To place our $[\text{CII}]$ measurement of MIPS J1428 in context, we compare the $[\text{CII}]$, CO, and FIR continuum emission from this source with that from other galaxies and Galactic sources. In Figure 3, we plot the $L_{[\text{CII}]} / L_{\text{FIR}}$ and $L_{\text{CO}(1 \rightarrow 0)} / L_{\text{FIR}}$ ratios for samples of Galactic star-forming regions and nearby gas-rich galaxies (Stacey et al. 1991), normal galaxies (Malhotra et al. 2001), local ULIRGs (Luhman et al. 2003), and MIPS J1428 and the three other high-redshift sources detected in $[\text{CII}]$ (Maiolino et al. 2005, 2009; Iono et al. 2006c). We estimate the $\text{CO}(1 \rightarrow 0)$ luminosity of MIPS J1428 assuming an $L'_{\text{CO}(2 \rightarrow 1)} / L'_{\text{CO}(1 \rightarrow 0)} = 0.9$ ratio intermediate between the ratios observed in local ULIRGs (≈ 0.7 ; Downes & Solomon 1998) and in starburst nuclei (≈ 1.1 ; Harrison et al. 1999; Weiß et al. 2005). For reference, we overplot the PDR model curves from Kaufman et al. (1999). A vector attached to the MIPS J1428 data point indicates how the measured ratios were adjusted for the PDR analysis in Section 3.2 (to account for non-PDR contributions to the $[\text{CII}]$ emission and optical depth effects in the CO transitions), and we further note that MIPS J1428 is placed in Figure 3 assuming an $L'_{\text{CO}(2 \rightarrow 1)} / L'_{\text{CO}(1 \rightarrow 0)}$ ratio $\approx 20\%$ lower than our best-fit PDR solution. We compare MIPS J1428 with each of the populations shown in Figure 3 in turn.

Stacey et al. (1991) study the $[\text{CII}]$ emission from the central regions of a sample of nearby galaxies, and find that the

$L_{[\text{CII}]} / L_{\text{CO}(1 \rightarrow 0)}$ and $L_{[\text{CII}]} / L_{\text{FIR}}$ ratios are sensitive tracers of the star formation activity in these sources. Starburst galaxies are well characterized by the same $L_{[\text{CII}]} / L_{\text{CO}(1 \rightarrow 0)} = 4100$ ratio seen in Galactic star-forming regions, which is a factor of ~ 3 times larger than in non-starburst galaxies and Galactic molecular clouds (Figure 3). However, the $L_{[\text{CII}]} / L_{\text{FIR}}$ ratios in starburst galaxies are higher than those observed in the most intense Galactic OB star formation regions. These results imply that while much of the molecular gas in a starburst nucleus is photodissociated by the FUV radiation from young stars, the very intense fields found in the most extreme Galactic star-forming regions are not providing the bulk of the luminosity. This picture is supported by PDR modeling, which indicates that the FUV fields producing the emission in the centers of starburst galaxies are intermediate in intensity between those producing the emission in non-starburst galaxies and those found in Galactic OB star formation regions (Figure 3). As the data point for MIPS J1428 falls near the high- G_0 end of the distribution of starburst points in Figure 3, we conclude that in MIPS J1428, like in nearby starburst nuclei, the bulk of the molecular gas is exposed to moderately intense FUV radiation produced by young stars.

Malhotra et al. (2001) observe $[\text{CII}]$ and other FIR fine-structure line emission from a sample of 60 normal galaxies with varying levels of star formation activity, which are all sufficiently distant that the FIR emission is contained within the $\approx 70''$ *Infrared Space Observatory*–Long-Wavelength Spectrometer beam. These authors find that the FIR continuum and much of the $[\text{CII}]$ emission arise from PDRs, which in many of their galaxies are characterized by similarly elevated values of G_0 as deduced here for MIPS J1428. However, the Malhotra et al. (2001) sources have lower $L_{[\text{CII}]} / L_{\text{CO}}$ ratios than MIPS J1428 or its starburst analogs, indicating that most of the CO emission is produced by molecular gas residing in less active star-forming regions than those that produce the fine-structure line emission. This difference helps reinforce our conclusion that in MIPS J1428 it is the entire galaxy, rather than just an active central region, that is host to vigorous star formation.

The median $L_{[\text{CII}]} / L_{\text{FIR}}$ ratio in local ULIRGs is a factor of ~ 7 times lower than in normal star-forming galaxies (Luhman et al. 2003) and a factor of ~ 4 times lower than in MIPS J1428. One possible explanation for this low ratio is that the $[\text{CII}]$ emission is produced in dense PDRs illuminated by intense FUV radiation (e.g., Papadopoulos et al. 2007), as indicated by the PDR model overlays in Figure 3. Alternatively, the $[\text{CII}]$ emission may originate in PDRs with more modest values of n and G_0 , but an additional source of FIR continuum emission may lower the global $L_{[\text{CII}]} / L_{\text{FIR}}$ ratio (Luhman et al. 2003; Abel et al. 2009). Regardless of the origins of the weak $[\text{CII}]$ emission in local ULIRGs, it is clear that these galaxies provide poor templates for MIPS J1428.

We also include the three high-redshift QSOs detected in $[\text{CII}]$ in Figure 3. SDSS J1148 has been detected in $\text{CO}(3 \rightarrow 2)$ and BRI 0952 in $\text{CO}(5 \rightarrow 4)$, and we use the measured $L'_{\text{CO}(3 \rightarrow 2)} / L'_{\text{CO}(1 \rightarrow 0)} = 0.72$ and modeled $L'_{\text{CO}(5 \rightarrow 4)} / L'_{\text{CO}(1 \rightarrow 0)} = 0.58$ ratios for Mrk 231 (Papadopoulos et al. 2007) to estimate the $\text{CO}(1 \rightarrow 0)$ luminosities for these sources. To account for the uncertainties in the CO excitation of high-redshift systems (e.g., Hainline et al. 2006), we show these data points with error bars corresponding to ± 0.2 dex and ± 0.3 dex, respectively. The low $L_{[\text{CII}]} / L_{\text{FIR}}$ and $L_{\text{CO}} / L_{\text{FIR}}$ ratios in SDSS J1148 and BR 1202N indicate similar physical conditions as in local ULIRGs. Indeed, Maiolino et al. (2005) found that the

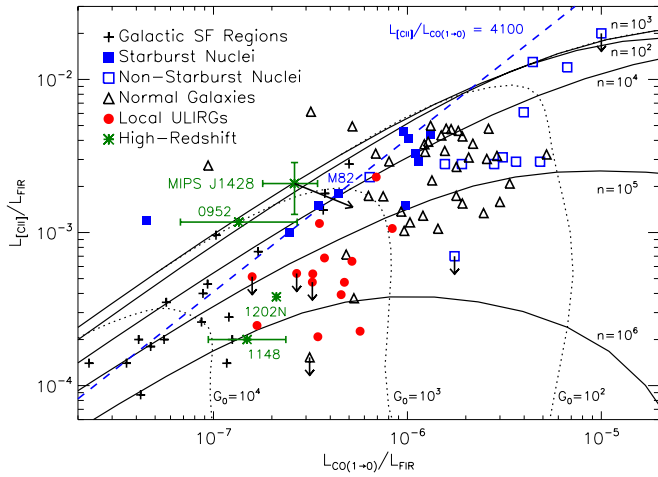


Figure 3. $L_{[\text{C II}]} / L_{\text{FIR}}$ vs. $L_{\text{CO}(1 \rightarrow 0)} / L_{\text{FIR}}$ for Galactic star-forming regions (crosses), starburst nuclei (filled squares), non-starburst nuclei (open squares), normal galaxies (triangles), local ULIRGs (circles), and high-redshift sources (asterisks). $\text{CO}(1 \rightarrow 0)$ luminosities of the normal galaxies and local ULIRGs are taken from the literature and from J. Graciá-Carpio et al. (2010, in preparation). $\text{CO}(1 \rightarrow 0)$ luminosities for MIPS J1428 and two of the other high-redshift sources are estimated from the measurements of higher- J lines as described in the text. Starburst galaxies and Galactic star-forming regions are characterized by $L_{[\text{C II}]} / L_{\text{CO}(1 \rightarrow 0)} \approx 4100$ (dashed). Overplotted are the PDR model calculations for gas density (n) and FUV field strength (G_0) from Kaufman et al. (1999), and a vector indicates how the MIPS J1428 data point was shifted for the PDR analysis in Section 3.2.

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[C II], CO, and FIR continuum emission of SDSS J1148 are consistent with a high-density, high- G_0 PDR, and Walter et al. (2009) showed that the star formation in this system is confined to a compact region with a high surface brightness comparable to that at the center of Arp 220. However, BRI 0952 has a larger $L_{[\text{C II}]} / L_{\text{FIR}}$ ratio and a $L_{[\text{C II}]} / L_{\text{CO}}$ ratio similar to that in MIPS J1428. We suggest that while SDSS J1148 and BR 1202N are likely dissimilar to MIPS J1428, the connection drawn here between MIPS J1428 and local starburst nuclei may also provide insight into the nature of the host galaxy of BRI 0952.

Finally, it is important to note that while we assume that the $L_{[\text{C II}]} / L_{\text{FIR}}$ and $L_{\text{CO}} / L_{\text{FIR}}$ ratios in MIPS J1428 are unaffected by the potential gravitational lensing, we cannot rule out the possibility that these ratios are altered by differential magnification. For example, one could construct a model in which the intrinsic emission ratios of MIPS J1428 are similar to those in local ULIRGs, but where the $L_{[\text{C II}]} / L_{\text{FIR}}$ ratio is enhanced by the relatively large magnification of a localized H II region that falls near a caustic. However, in the absence of other evidence supporting such a scenario, we assume that the measured flux ratios are equal to the intrinsic luminosity ratios.

4.2. MIPS J1428 as an Extended Starburst

The molecular gas in MIPS J1428 is exposed to similar UV radiation fields and has similar excitation as the gas in the central region of a typical starburst galaxy. We therefore suggest that MIPS J1428 may be modeled as a scaled-up version of a starburst nucleus. As an example, we consider scaling up the central region of the prototypical starburst galaxy M82 in such a manner as to match the much larger luminosity of MIPS J1428, while at the same time conserving the strength of the characteristic FUV radiation field that controls the PDR emission. We assume that in a starburst environment this characteristic field is determined by the global star formation

density, rather than by the purely local properties of the interactions between individual star clusters and their natal molecular clouds. This interpretation was adopted for M82 and NGC 253 based on multiple-line PDR analysis (Wolfire et al. 1990; Carral et al. 1994; Lord et al. 1996), and is also motivated by the nonlinear relation between $I_{[\text{C II}]}$ and I_{FIR} observed in larger samples of galactic nuclei (Crawford et al. 1985; Stacey et al. 1991).

For a starburst region in which young stellar clusters and molecular clouds are randomly distributed, Wolfire et al. (1990) modeled the relationship between the average FUV flux incident on the molecular gas (G_0), and the size (D) and total luminosity (L_{IR}) of the region. This relationship depends on the mean free path of an FUV photon (λ), but in the limits of $\lambda \ll D$ and $\lambda \gg D$ these models give $G_0 \propto \lambda L_{\text{IR}} / D^3$ and $G_0 \propto L_{\text{IR}} / D^2$, respectively. Adopting $L_{\text{IR}} \sim 3 \times 10^{10} L_{\odot}$ for the central $D \sim 300$ pc starburst region of M82 (Telesco & Harper 1980; Joy et al. 1987), and assuming that MIPS J1428 and M82 have similar λ and the same average G_0 (Figure 3), the factor of $\sim 1000 \mu^{-1}$ greater luminosity of MIPS J1428 then translates into a size scale of $D \approx 3 \mu^{-1/3} - 10 \mu^{-1/2}$ kpc. In short, if the large luminosity of MIPS J1428 is produced by only moderate-intensity radiation, the star formation generating this radiation must be extended over a large area.

While MIPS J1428 remains unresolved in dust continuum and molecular gas emission, integral field spectroscopy shows H α emission extended over $\approx 0.7''$ (≈ 6 kpc; Swinbank et al. 2006). This result is consistent with our interpretation of MIPS J1428 as a source powered by extended star formation, although the degree to which the H α image is distorted by the foreground lens, or by the presence of large and spatially varying extinction, is unknown. Further interpretation of the connection between the bright [C II] emission in MIPS J1428 and the potentially large extent of the star formation will benefit from a size measurement in an extinction-free tracer and better constraints on the lensing magnification.

If MIPS J1428 is indeed powered by a starburst extending over several kiloparsecs, this would be in sharp contrast to local ULIRGs, in which most of the emission traced by CO interferometry is contained within the central ~ 1 kpc (Downes & Solomon 1998). However, there is ample evidence that the most luminous star-forming galaxies at higher redshifts are more extended. The best-studied sample of such sources are the SMGs, which like MIPS J1428 are submillimeter-bright galaxies with luminosities of $L_{\text{IR}} \sim 10^{13} L_{\odot}$ that are generated predominantly by star formation (Alexander et al. 2005). Interferometric imaging of the radio continuum of $z = 1-3$ SMGs has shown that many of these sources have detectable emission extended over ~ 10 kpc (Chapman et al. 2004) and that the population has a median FWHM size of ~ 5 kpc (Biggs & Ivison 2008). Similarly, many of the SMGs studied by Tacconi et al. (2006, 2008) have CO FWHM sizes of ~ 4 kpc. The model of extended star formation we suggest here for MIPS J1428 is therefore consistent with the large sizes of SMGs, which indicate that the most luminous star-forming galaxies at $z = 1-3$ are powered by starbursts extending over much larger regions than in local systems.

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