The Astrophysical Journal, 504:L11–L15, 1998 September 1

INFRARED SPACE OBSERVATORY[1] MEASUREMENTS OF A [C II] 158 MICRON LINE DEFICIT IN ULTRALUMINOUS INFRARED GALAXIES

M. L. Luhman,[2,3] S. Satyapal,[4,5] J. Fischer,[2] M. G. Wolfire,[6,7] P. Cox,[8]
S. D. Lord,[9] H. A. Smith,[10] G. J. Stacey,[11] and S. J. Unger[12]
Received 1998 April 29; accepted 1998 June 4; published 1998 July 23

ABSTRACT

We report measurements of the [C II] 157.74 μm fine-structure line in a sample of seven ultraluminous infrared galaxies (ULIGs) ($L_{\rm IR} > 10^{12}\ L_\odot$) with the Long Wavelength Spectrometer on the *Infrared Space Observatory*. The [C II] line is an important coolant in galaxies and arises in interstellar gas exposed to far-ultraviolet photons ($h\nu \geq 11.26$ eV); in ULIGs, this radiation stems from the bursts of star formation and/or from the active galactic nuclei that power the tremendous infrared luminosity. The [C II] 158 μm line is detected in four of the seven ULIGs; the absolute line flux (about a few times 10^{-20} W cm^{-2}) represents some of the faintest extragalactic [C II] emission yet observed. Relative to the far-infrared continuum, the [C II] flux from the observed ULIGs is ~10% of that seen from nearby normal and starburst galaxies. We discuss possible causes for the [C II] deficit, namely (1) self-absorbed or optically thick [C II] emission, (2) saturation of the [C II] emission in photodissociated gas with high gas density n ($\gg 3 \times 10^3$ cm^{-3}) or with a high ratio of incident UV flux G_0 to n ($G_0/n \gtrsim 10$ cm^3), or (3) the presence of a soft ultraviolet radiation field caused, for example, by a stellar population deficient in massive main-sequence stars. As nearby examples of colliding galaxies, ULIGs may resemble high-redshift protogalaxies in both morphology and spectral behavior. If true, the suggested [C II] deficit in ULIGs poses limitations on the detection rate of high-z sources and on the usefulness of [C II] as an eventual tracer of protogalaxies.

Subject headings: galaxies: active — galaxies: ISM — galaxies: starburst — infrared: galaxies — infrared: ISM: lines and bands — ISM: atoms

1. INTRODUCTION

The 157.74 μm $^2P_{3/2} \rightarrow {}^2P_{1/2}$ fine-structure line of C^+ is the single brightest emission line in the spectrum of most galaxies, providing as much as 1% of the total far-infrared (FIR) luminosity (see, e.g., Stacey et al. 1991b and references therein). In the interstellar medium (ISM) of galaxies, the [C II] 158 μm line traces gas exposed to stellar far-ultraviolet (far-UV) photons with energy greater than 11.26 eV, the ionization potential of neutral carbon. In such regions, atomic hydrogen and electrons collisionally excite ground-state C^+ ions, producing [C II] radiation that cools the gas. The [C II] transition has a critical density $n_{\rm cr}$ of 3×10^3 and 50 cm^{-3} for collisions with hydrogen and electrons, respectively (Flower & Launay 1977; Hayes & Nussbaumer 1984), and modest energy requirements for excitation, i.e., $T_{\rm level} \sim 92$ K above the ground state. These attributes, combined with a high abundance of interstellar carbon (e.g., C/H = 1.4×10^{-4}; Sofia et al. 1997), make the [C II] line the dominant coolant in UV-exposed atomic gas over a wide range of physical conditions (Hollenbach, Takahashi, & Tielens 1991; Wolfire et al. 1995). Such environments include much of the warm ($T \gtrsim 100$ K), dense ($n \geq 100$ cm^{-3}) atomic ISM between H II regions and molecular clouds, i.e., photodissociation regions (PDRs), as well as the cold ($T \lesssim 50$ K), diffuse phases of the ISM. The [C II] line can also be produced in the warm ($T \sim 8000$ K) neutral ($n_e/n \sim 0.1$) and ionized ($n_e/n \sim 1$) diffuse phases.

As examples of gas-rich galaxies characterized by strong star formation activity, ultraluminous infrared galaxies (ULIGs) ($L_{\rm IR} > 10^{12}\ L_\odot$) seem to offer the prime ingredients for bright [C II] emission. The tremendous infrared (IR) luminosity of ULIGs is ~10^3 times that of the Milky Way Galaxy and is thought to be due to enhanced star formation ("starburst") and/or an active galactic nucleus (AGN), which produces UV radiation that is absorbed by dust and reradiated in the IR. The starburst and/or AGN form as a result of the merger of two gas-rich spiral galaxies, thereby creating a large concentration of molecular gas ($M_{\rm H_2} > 10^{10}\ M_\odot$) in the core which fuels the starburst and AGN (e.g., Norman & Scoville 1988). The starburst/AGN activity likely dominates the excitation and global energetics of all phases of the ISM in these galaxies.

To compare the ISM in ULIGs with that in less luminous galaxies, we have acquired spectra of the [C II] 158 μm line in ULIGs using the Long Wavelength Spectrometer (LWS) (Clegg et al. 1996) on the *Infrared Space Observatory* (*ISO*) (Kessler et al. 1996). In addition to tracing the multiphase ISM, the FIR [C II] line, compared to optical lines, for example, is much less affected by the high extinction ($A_V \gtrsim 1000$; Sanders & Mirabel 1996) typical of the heavily obscured nuclear regions in ULIGs. The observations presented here constitute part of the LWS consortium guaranteed-time "Central Program" on IR-bright galaxies. In a future paper, we will discuss the results of an ongoing *ISO* study that examines the [C II] emission in

[1] Based on observations with *ISO*, an ESA project with instruments funded by ESA Member States (especially the PI countries: France, Germany, the Netherlands, and the United Kingdom) with the participation of ISAS and NASA.

[2] Naval Research Laboratory, Remote Sensing Division, Code 7217, Washington, DC 20375.
[3] NRC-NRL Research Associate.
[4] NASA Goddard Space Flight Center, Greenbelt, MD 20771.
[5] NRC-NASA Research Associate.
[6] University of Maryland, Department of Astronomy, College Park, MD 20742.
[7] Towson University, Department of Physics, Towson, MD 21252.
[8] Institut d' Astrophysique Spatiale, Université de Paris XI, Orsay, France.
[9] IPAC, California Institute of Technology, Pasadena, CA 91125.
[10] Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138.
[11] Cornell University, Astronomy Department, Ithaca, NY 14853.
[12] Queen and Mary Westfield College, University of London, London, UK.

Report Documentation Page	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE **1998**	2. REPORT TYPE	3. DATES COVERED **00-00-1998 to 00-00-1998**

4. TITLE AND SUBTITLE **Infrared Space Observatory Measurements of a [C II] 158 micron Line Deficit in Ultraluminous Infrared Galaxies**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Research Laboratory,Code 7217,4555 Overlook Avenue, SW,Washington,DC,20375**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S)
	11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**		**5**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

TABLE 1
OBSERVING LOG

Source	α_{2000}	δ_{2000}	AOT[a]	Observation Date
Arp 299	11 28 32.3	+58 33 43.4	LWS01	1996 May 15
IRAS 12071−0444	12 09 45.3	−05 01 13.3	LWS02	1996 Jul 19
Mrk 231	12 56 14.2	+56 52 24.9	LWS01	1996 May 15
IRAS 15206+3342	15 22 38.1	+33 31 33.3	LWS02	1997 Sep 5
IRAS 15250+3609	15 26 59.3	+35 58 37.2	LWS02	1996 Sep 20
Arp 220	15 34 57.2	+23 30 11.2	LWS01	1996 Aug 20
NGC 6240	16 52 58.8	+02 24 04.3	LWS01	1996 Aug 21
IRAS 22491−1808	22 51 49.3	−17 52 24.1	LWS02	1996 May 21
IRAS 23365+3604	23 39 01.2	+36 21 10.0	LWS02	1997 Dec 7

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

[a] AOT = Astronomical Observation Template. LWS01 = medium-resolution ($R \sim 200$) spectrum covering the full 43–197 μm range of the LWS; LWS02 = medium-resolution line spectrum, in this case with a 3.4 μm width and centered on the [C II] line wavelength.

an added sample of ULIGs and follows up on our initial guaranteed-time program. Here, we also include for purposes of comparison *ISO* [C II] measurements for two luminous IR galaxies, Arp 299 and NGC 6240 ($L_{IR} = 8$ and 7×10^{11} $L_\odot$; Sanders, Scoville, & Soifer 1991), which are examples of colliding galaxies but are slightly less luminous than the ULIGs.

2. OBSERVATIONS AND RESULTS

In Table 1, we summarize the observing log for the ULIGs, along with Arp 299 and NGC 6240, included in the *ISO* LWS consortium Central Program on IR-bright galaxies. Observations of the [C II] 158 μm fine-structure line in each of the galaxies used the *ISO* LWS medium-resolution ($\Delta\lambda = 0.6$ μm at 158 μm) grating mode (Clegg et al. 1996). For the brighter sources ($F_{100\,\mu\mathrm{m}} > 25$ Jy), we obtained full 43–197 μm spectra, from which we extracted [C II] spectra. For the fainter objects, we acquired spectra in the vicinity of the [C II] line only.

We co-added processed spectral scans, extracted line profiles, and measured line fluxes and uncertainties using the *ISO* Spectral Analysis Package (ISAP) and IRAF. Pipeline processing of LWS spectra performs wavelength and flux calibration, removes cosmic-ray glitches, subtracts dark current, and corrects for instrumental responsivity variations (Swinyard et al. 1996). In Table 2, we list the measured [C II] line fluxes with the statistical errors and 3 σ flux upper limits, where, in all cases, the line was unresolved. The upper limits were calculated assuming a Gaussian line with the effective instrumental profile and a 3 σ amplitude. When detected, the [C II] line appeared at the expected wavelength adjusted for redshift. At the redshifted wavelengths of the [C II] line, the [C II] measurements are uncontaminated by Galactic [C II] emission for all sources. Uncertainties in the flux measurements were dominated by flux calibration errors arising from uncorrected fluctuations of detector responsivities with time and inaccurate dark current subtraction. These errors are estimated at $\pm 25\%$ based on overlapping data in neighboring detectors from the full grating scans. The LWS beam size is 69″ at 158 μm (Burgdorf et al. 1997). All sources in this study were spatially unresolved, with the beam encompassing all of the IR emission. For each source, we list in Table 2 the FIR flux F_{FIR}, defined here as the emission from 42.5 to 122.5 μm as measured by IRAS and computed according to the formula $F_{FIR} = 1.26 \times 10^{-18}$ [2.58 $F_\nu(60$ μm) $+ F_\nu(100$ μm)] W cm^{-2}, where $F_\nu(60$ μm) and $F_\nu(100$ μm) are the flux densities in janskys at 60 and 100 μm, respectively (Helou et al. 1988).

As shown in Table 2, the [C II] line has been detected in four of the seven ULIGs observed to date, plus Arp 299 and NGC 6240. The absolute [C II] fluxes are among the faintest extragalactic [C II] emission yet seen. In Figure 1, we plot the [C II] line fluxes against the FIR flux for the sample ULIGs, Arp 299, and NGC 6240, and for an assortment of normal and starburst galaxies presented in a study by Lord et al. (1996). The FIR flux is defined as described above for both the ULIG and normal/starburst galaxy samples.

3. DISCUSSION

Observations reveal that a [C II]–to–FIR continuum ratio of 0.1%–1% characterizes virtually all normal and starburst galaxies (i.e., Crawford et al. 1985; Stacey et al. 1991b), as illustrated in Figure 1. For normal and starburst galaxies, dense

TABLE 2
SAMPLE PROPERTIES AND MEASURED [C II] FLUX

Source	Redshift	log ($L_{IR}/L_\odot$)[a]	$F_\nu(60$ μm)	$F_\nu(100$ μm)	F_{FIR}	$F_{[C\,II]\,158\,\mu m}$
Arp 299	0.104	11.91	103.7	107.4	4720	8.81 ± 0.16
IRAS 12071−0444	0.128	12.29	2.46	2.47	111	<0.05
Mrk 231	0.042	12.54	31.99	30.29	1420	0.32 ± 0.04
IRAS 15206+3342	0.124	12.18	1.77	1.89	81.2	0.20 ± 0.03
IRAS 15250+3609	0.055	12.00	7.29	5.91	311	<0.14
Arp 220	0.018	12.19	103.8	112.4	4790	0.87 ± 0.04
NGC 6240	0.024	11.82	22.68	27.78	1090	2.57 ± 0.03
IRAS 22491−1808	0.078	12.10	5.44	4.45	232	<0.12
IRAS 23365+3604	0.065	12.13	7.09	8.36	336	0.122 ± 0.018

NOTE.—$F_\nu(60$ μm) and $F_\nu(100$ μm) are from IRAS measurements in units of janskys. F_{FIR} and $F_{[C\,II]\,158\,\mu m}$ are in units of 10^{-19} W cm^{-2}. Flux upper limits are 3 σ.

[a] L_{IR} defined in the literature as the IR luminosity from 8–1000 μm; data from Sanders et al. 1988a, 1988b, 1991 and Murphy et al. 1996.

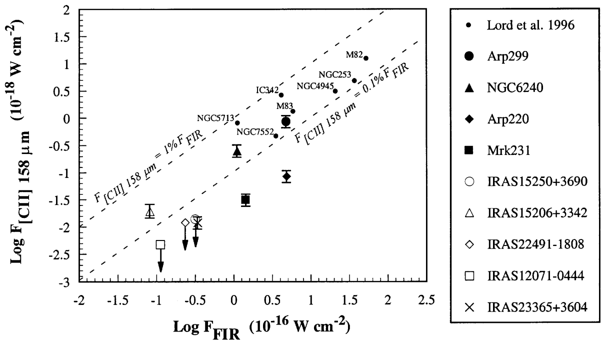

FIG. 1.—The [C II] 158 μm line flux plotted against the FIR flux for the ULIGs in this study plus Arp 299 and NGC 6240 and for a sample of normal/starburst galaxies taken from Lord et al. (1996). The error bars shown denote the [C II] flux calibration uncertainties, which are much greater than the statistical errors. The two dashed lines depict the observed $F_{[\mathrm{C\,II}]}/F_{\mathrm{FIR}}$ regime typical of normal and starburst galaxies.

($n \geq 100$ cm^{-3}) PDRs exposed to far-UV photons from OB stars often dominate the global [C II] luminosity (e.g., Stacey et al. 1991b). Even for galaxies, such as the Milky Way and other normal spirals, with significant [C II] emission from the extended low-density warm ionized medium and/or the cold neutral medium, $F_{[\mathrm{C\,II}]}/F_{\mathrm{FIR}}$ still ranges from 0.1% to 1% (Madden et al. 1993; Bennett et al. 1994; Heiles 1994). To date, Malhotra et al. (1997) report the only published exceptions among normal and starburst galaxies with ratios significantly below 0.1%, where, in a sample of 30 normal star-forming galaxies, three FIR-bright sources ($L_{\mathrm{FIR}} \sim 10^{10}$ $L_\odot$) show $L_{[\mathrm{C\,II}]}/L_{\mathrm{FIR}} < 2 \times 10^{-4}$.

Based on the sources in this study, we find that the [C II] emission relative to the FIR flux in ULIGs is generally only 10% of that seen in normal and starburst galaxies (see Fig. 1). For six of the seven ULIGs observed to date, $F_{[\mathrm{C\,II}]}/F_{\mathrm{FIR}}$ is less than 5×10^{-4}, with Arp 220 showing the lowest measured ratio among our sample of 1.8×10^{-4}. By comparison, Arp 299 and NGC 6240 display [C II]–to–FIR continuum ratios consistent with other starburst nuclei, even though they are only slightly less luminous mergers than the ULIGs. IRAS 15206+3342 is the only ULIG presented here with no [C II] deficit ($F_{[\mathrm{C\,II}]}/F_{\mathrm{FIR}} = 2.5 \times 10^{-3}$). This ULIG is a Seyfert 2 galaxy exhibiting "warm" FIR colors of $F_\nu(25\ \mu\mathrm{m})/F_\nu(60\ \mu\mathrm{m}) = 0.2$ and $F_\nu(60\ \mu\mathrm{m})/F_\nu(100\ \mu\mathrm{m}) = 0.9$ (Sanders et al. 1988b); these traits are not unlike those of other ULIGs in our sample, which would suggest that, within the ULIG class, the [C II] deficit does not depend on IR luminosity, FIR color temperature, or optical spectral type.

In the *ISO* LWS FIR spectra of Arp 220 and Mrk 231, the weak [C II] line is accompanied by other weak (undetected) fine-structure lines from the ionized and PDR gas (Fischer et al. 1997a, 1997b, 1998). These lines include [O III] 52, 88 μm, [N III] 57 μm, [N II] 122 μm, and [O I] 63, 146 μm, and, like [C II], are generally strong in the FIR spectra of starburst galaxies such as Arp 299 (e.g., Satyapal et al. 1998). A comparison of the relative strengths of lines in the mid- to far-IR spectra of Arp 220 suggests that the extinction at 158 μm is too low to explain the weak [C II] line emission (Fischer et al. 1997a, 1997b, 1998). With this in mind, we consider the following possible explanations for the [C II] deficiency.

Self-absorbed or optically thick [C II].—Self-absorption of [C II] by cooler foreground material or optically thick [C II] emission could weaken the observed [C II] relative to FIR in the ULIGs. In Arp 220, for example, Fischer et al. (1997a, 1997b) report self-absorption of the [O I] 63 μm line, which is a strong PDR cooling line like [C II]. In our Galaxy, partial self-absorption of [C II] has been recently detected toward the molecular cloud associated with the NGC 3576 H II region (Boreiko & Betz 1997) and toward SgrB2 using the *ISO* LWS Fabry-Perot interferometer (Cox et al. 1998). These observations suggest that, particularly for edge-on geometries, [C II] self-absorption could be important in ULIGs.

Although [C II] is generally optically thin in the Galactic ISM (e.g., Stacey et al. 1991a), optically thick [C II], i.e., $\tau_{[\mathrm{C\,II}]\ 158\ \mu\mathrm{m}} \geq 2$, could explain the observed ULIG $F_{[\mathrm{C\,II}]}/F_{\mathrm{FIR}}$. Assuming a velocity width of 100–300 km s^{-1} and $N_{\mathrm{C^+}}/N_{\mathrm{H}} = 1.4 \times 10^{-4}$, an optical depth in the [C II] line of 2 or greater is reached for column densities $N_{\mathrm{H}} \geq (2–6) \times 10^{23}$ cm^{-2}, or an $A_V \geq 130–390$ *in the PDR* (C$^+$) *gas alone.* Such a large A_V disagrees with the predictions of one-dimensional PDR models which generally show that the [C II] emission arises from a thin surface layer with $A_V \lesssim 4$ (e.g., Tielens & Hollenbach 1985). Additionally, recent *ISO* mid-IR line measurements suggest a *total* A_V of ~50 toward the starburst region in Arp 220 (Sturm et al. 1996), i.e., the presumed site of the [C II] emission, again inconsistent with an $A_V \geq 130–390$ just in the PDR zone.

Saturation of [C II].—For very high density ($n \gg n_{\mathrm{cr}}$ for [C II] $= 3 \times 10^3$ cm^{-3}) PDRs or for PDRs with a high ratio of UV flux to gas density ($G_0/n \gtrsim 10$ cm^3, where G_0 is normalized to the solar neighborhood radiation field; Habing 1968), theoretical PDR models show that $I_{[\mathrm{C\,II}]}$ saturates relative to I_{FIR} such that $I_{[\mathrm{C\,II}]}/I_{\mathrm{FIR}}$ can obtain values of 10^{-4} or less (e.g., Wolfire, Tielens, & Hollenbach 1990; Kaufman et al. 1998). In the high-density case where n lies well above the [C II] critical density, the abundance of C$^+$ in the upper level is fixed by the atomic statistical weights. In addition, the column density of C$^+$ becomes insensitive to the incident UV field (Wolfire, Hollenbach, & Tielens 1989). Since both the abundance and column density ceases to rise with n and G_0, the emergent [C II] line intensity saturates. Within a PDR, gas heating mainly occurs via the ejection of energetic electrons from dust grains exposed to UV photons. In the high G_0/n regime, the high incident UV flux increases the positive charge of the grain, thereby reducing the energy of the ejected photoelectrons. Thus, positively-charged grains reduce the fraction of UV photon energy that is converted to gas heating, which causes the [C II] line cooling to fall. In the Galaxy, [C II] line saturation is seen toward the high-n, high-G_0 PDRs associated with Orion-like H II regions, which have small [C II]–to–FIR continuum ratios of about a few times 10^{-4} (Russell et al. 1980, 1981).

Based on a decreasing trend in $F_{[\mathrm{C\,II}]}/F_{\mathrm{FIR}}$ with increasing $F_\nu(60\ \mu\mathrm{m})/F_\nu(100\ \mu\mathrm{m})$, i.e., increasing T_{dust} or G_0, Malhotra et al. (1997) suggest that a high G_0/n PDR could account for the [C II] deficit in three FIR-bright galaxies. For the ULIGs observed to date, we see no such trend within our sample, although, as with the Malhotra et al. FIR-bright galaxies, the ULIGs as a whole are characterized by low $F_{[\mathrm{C\,II}]}/F_{\mathrm{FIR}}$ and high (greater than 0.8) $F_\nu(60\ \mu\mathrm{m})/F_\nu(100\ \mu\mathrm{m})$. In Arp 220, we compared the relative strengths of the [O I] 146 μm line flux upper limit (Fischer et al. 1997b) and the [C II] and FIR fluxes to the predictions of the PDR models of Kaufman et al. (1998) and derived two solutions for n and G_0: (1) $n \sim 200$ cm^{-3}, $G_0 \sim 3 \times 10^3$ ($G_0/n \sim 15$ cm^3) and (2) $n \sim 10^5$ cm^{-3}, $G_0 \sim 5$ ($G_0/n \sim 5 \times 10^{-5}$ cm^3). By comparison, other normal and starburst galaxies are typically characterized by $G_0/n \sim 0.1–1$ cm^3 (e.g., Wolfire et al. 1990; Carral et al. 1994; Fischer et al. 1996), which suggests that if [C II] line saturation alone accounts for the low $F_{[C\,II]}/F_{FIR}$, then the PDR physical conditions in ULIGs differ greatly from those found in other galaxies.

Soft UV radiation field.—A stellar population deficient in massive main-sequence stars, either due to an aging starburst or an initial mass function with a low upper mass cutoff, could also give rise to a soft UV field and, consequently, a small $F_{[C\,II]}/F_{FIR}$ (e.g., Satyapal et al. 1997). In this case, radiation from cool ($T_{eff} \lesssim 20{,}000$ K) stars heats the dust but contains fewer UV photons. Thus, according to PDR models (Spaans et al. 1994), gas heating is reduced due to the lower rate of photoelectrons ejected from grains. In addition, the column density of C^+ in a PDR is reduced as the atomic/molecular transition layer moves closer to the cloud surface. The net effect reduces the size and luminosity of the [C II]–emitting region. If the [C II] deficit results from an age effect, then there must naturally exist ULIGs, such as IRAS 15206+3342, with no [C II] deficit that presumably contain young starbursts. Likewise, an unusually high dust-to-gas ratio could diminish the UV flux as felt by the gas, since the dust would compete more efficiently with the gas for the available UV photons. This effect would decrease the extent of the PDR gas and thus would lower $L_{[C\,II]}/L_{FIR}$, just as observations of low-metallicity galaxies show that the paucity of dust can, conversely, increase $L_{[C\,II]}/L_{FIR}$ as a result of the greater penetration depth of the UV photons (e.g., Israel et al. 1996; Madden et al. 1997). Compared to a population of cool stars, a high abundance of dust in the immediate vicinity of the starburst/AGN is more consistent with the warmer FIR colors of ULIGs, although some unknown mechanism for increasing the dust-to-gas ratio is required. Unlike the aforementioned explanations for the [C II] deficit, a soft or severely-attenuated UV field could also explain the lack of FIR [O III] lines in the *ISO* LWS spectra of Arp 220 and Mrk 231 by reducing the line emission from the ionized gas as well (Fischer et al. 1997a, 1997b, 1998).

4. IMPLICATIONS

As examples of colliding galaxies, the observed ULIGs likely represent local analogs of high-z ($\gtrsim 2$) protogalaxies. If galaxies form from the coalescence of smaller structures, then protogalaxies at redshifts from 1 to 10 should resemble the disturbed ULIGs at low z, a suggestion that is supported by the appearance of the faintest sources in the Hubble Deep Field image (e.g., Mobasher, Rowan-Robinson, & Georgakakis 1996; van den Bergh et al. 1996). As the brightest line in the spectrum of most galaxies, the [C II] 158 μm line is a potentially powerful spectroscopic tracer of these high-z objects, where for $z = 2$–6, the [C II] line is shifted to submillimeter wavelengths. Recent derivations of the [C II] luminosity in protogalaxies as a function of z suggest that it may be possible to detect as many as 200 protogalaxies per winter from the South Pole with a 10 m telescope (Stark 1997). Such an estimate assumes, however, that $L_{[C\,II]} \sim 0.2\% L_{gal}$ from observations of nearby starburst galaxies. The much smaller $L_{[C\,II]}/L_{gal}$ ratio implied by the ULIG observations presented here would render problematic such ground-based submillimeter observations. The absence of submillimeter [C II] emission from the $z = 4.69$ QSO BR1033−0327 would seem to support this suggestion (Isaak et al. 1994). Thus, the [C II]–to–FIR continuum ratio specific to ULIGs and more generally to protogalaxies has a direct impact on the feasibility and interpretation of future submillimeter spectroscopic surveys from the ground or from space. In the future, we will combine the [C II] data presented in this study with other *ISO* [C II] observations of ULIGs to explore further the usefulness of [C II] as a probe of high-z galaxies and, ultimately, as a diagnostic of galaxy formation models.

The authors would like to acknowledge the support of the Office of Naval Research, the Smithsonian Garber Fellowship program, the NASA *ISO* program, and NASA grant NAGW-1711.

REFERENCES

Bennett, C. L., et al. 1994, ApJ, 434, 587
Boreiko, R. T., & Betz, A. L. 1997, ApJS, 111, 409
Burgdorf, M., et al. 1997, in the Proc. First *ISO* Workshop on Analytical Spectroscopy, ed. A. M. Heras, K. Leech, N. R. Trams, & M. Perry (ESA SP-419; Noordwijk: ESA), 51
Carral, P., Hollenbach, D. J., Lord, S. D., Colgan, S. W. J., Haas, M. R., Rubin, R. H., & Erickson, E. F. 1994, ApJ, 423, 223
Clegg, P. E., et al. 1996, A&A, 315, L38
Cox, P., et al. 1998, in preparation
Crawford, M. K., Genzel, R., Townes, C. H., & Watson, D. M. 1985, ApJ, 291, 755
Fischer, J., et al. 1996, A&A, 315, L97
———. 1997a, in Proc. First *ISO* Workshop on Analytical Spectroscopy, ed. A. M. Heras, K. Leech, N. R. Trams, & M. Perry (ESA SP-419; Noordwijk: ESA),149
———. 1997b, in Extragalactic Astronomy in the Infrared: Proc. XVIIth Recontres de Moriond Series, ed. G. A. Mamon, T. X. Thuan, & J. T. T. Van (Paris: Editions Frontières), 289
———. 1998, in preparation
Flower, D. R., & Launay, J. M. 1977, J. Phys. B, 10, 3673
Habing, H. J. 1968, Bull. Astron. Inst. Netherlands, 19, 421
Hayes, M. A., & Nussbaumer, H. 1984, A&A, 134, 193
Heiles, C. 1994, ApJ, 436, 720
Helou, G., Khan, I. R., Malek, L., & Boehmer, L. 1988, ApJS, 68, 151
Hollenbach, D., Takahashi, T., & Tielens, A. G. G. M. 1991, ApJ, 377, 192
Isaak, K. G., McMahon, R. G., Hills, R. E., & Withington, S. 1994, MNRAS, 269, L28
Israel, F. P., Maloney, P. R., Geis, N., Herrmann, F., Madden, S. C., Poglitsch, A., & Stacey, G. J. 1996, ApJ, 465, 738
Kaufman, M., Wolfire, M. G., Hollenbach, D., & Luhman, M. L. 1998, in preparation
Kessler, M. F., et al. 1996, A&A, 315, L27
Lord, S. D., et al. 1996, A&A, 315, L117
Madden, S. C., Geis, N., Genzel, R., Herrmann, F., Jackson, J., Poglitsch, A., Stacey, G. J., & Townes, C. H. 1993, ApJ, 407, 579
Madden, S. C., Poglitsch, A., Geis, N., Stacey, G. J., & Townes, C. H. 1997, ApJ, 483, 200
Malhotra, S., et al. 1997, ApJ, 491, L27
Mobasher, B., Rowan-Robinson, M., & Georgakakis, A. 1996, MNRAS, 282, 7
Murphy, T. W., Jr., Armus, L., Matthews, K., Soifer, B. T., Mazzarella, J. M., Shupe, D. L., Strauss, M. A., & Neugebauer, G. 1996, AJ, 111, 1025
Norman, C., & Scoville, N. 1988, ApJ, 332, 124
Russell, R. W., Melnick, G., Gull, G. E., & Harwit, M. 1980, ApJ, 240, L99
Russell, R. W., Melnick, G., Smyers, S. D., Kurtz, N. T., Gosnell, T. R., Harwit, M., & Werner, M. W. 1981, ApJ, 250, L35
Sanders, D. B., & Mirabel, I. F. 1996, ARA&A, 34, 749
Sanders, D. B., Scoville, N. Z., & Soifer, B. T. 1991, ApJ, 370, 158
Sanders, D. B., Soifer, B. T., Elias, J. H., Madore, B. F., Matthews, K., Neugebauer, G., & Scoville, N. Z. 1988a, ApJ, 325, 74
Sanders, D. B., Soifer, B. T., Elias, J. H., Neugebauer, G., & Matthews, K. 1988b, ApJ, 328, L35
Satyapal, S., et al. 1998, in preparation
Satyapal, S., Luhman, M. L., Fischer, J., Greenhouse, M. A., & Wolfire, M. G. 1997, in Proc. First *ISO* Workshop on Analytical Spectroscopy, ed. A. M. Heras, K. Leech, N. R. Trams, & M. Perry (ESA SP-419; Noordwijk: ESA), 293
Sofia, U. J., Cardelli, J. A., Guerin, K. P., & Meyer, D. M. 1997, ApJ, 482, 105
Spaans, M., Tielens, A. G. G. M., van Dishoeck, E. F., & Bakes, E. L. O. 1994, ApJ, 437, 270

Stacey, G. J., Geis, N., Genzel, R., Jackson, J. M., Madden, S. C., Poglitsch, A., & Townes, C. H. 1991a, ApJ, 382, L37
Stacey, G. J., Geis, N., Genzel, R., Lugten, J. B., Poglitsch, A., Sternberg, A., & Townes, C. H. 1991b, ApJ, 373, 423
Stark, A. A. 1997, ApJ, 481, 587
Sturm, E., et al. 1996, A&A, 315, L133
Swinyard, B. M., et al. 1996, A&A, 315, L43
Tielens, A. G. G. M., & Hollenbach, D. 1985, ApJ, 291, 722
van den Bergh, S., Abraham, R. G., Ellis, R. S., Tanvir, N. R., Santiago, B. X., & Glazebrook, K. G. 1996, AJ, 112, 359
Wolfire, M. G., Hollenbach, D., McKee, C., Tielens, A. G. G. M., & Bakes, E. L. O. 1995, ApJ, 443, 152
Wolfire, M. G., Hollenbach, D., & Tielens, A. G. G. M. 1989, ApJ, 344, 770
Wolfire, M. G., Tielens, A. G. G. M., & Hollenbach, D. J. 1990, ApJ, 358, 116